*International Journal of Fluid Power 2 (2001) No. 2 pp. 5-36*

**REVIEW PAPER**

# AN OVERVIEW OF MAGNETO- AND ELECTRO-RHEOLOGICAL FLUIDS AND THEIR APPLICATIONS IN FLUID POWER SYSTEMS

**Ashish Agrawal, Prashant Kulkarni, Sheila L. Vieira and Nagi G. Naganathan**

*M.I.M.E Department, University of Toledo, 4005 Nitschke Hall, 2801 West Bancroft St., Toledo, OH 43606, USA*
*nagi.naganathan@utoledo.edu*

**Abstract**

The rapid change in viscosity of magnetorheological (MR) and electrorheological (ER) fluids subjected to a magnetic or an electric field, respectively, has attracted the attention of many researchers. However, as MR fluids show higher yield stress than ER fluids, they have merited more attention during the last few years. In this paper we present an overview of magneto- and electrorheological fluids, their basic properties, behaviour under different flow types and their uses in fluid power systems, among others.

**Keywords:** magnetorheological fluids, electrorheological fluids, smart materials, fluid power

## 1 Introduction

Certain fluids when exposed to a magnetic or an electric field exhibit a remarkable change in their rheological behaviour. First described by Rabinow (1948) and Winslow (1949), these materials have a great potential in applications such as torque transfer devices, damping systems, brakes and so on.

The family of magnetic field dependent fluids includes ferrofluids, magnetorheological fluids, magnetic powders and magnetorheological elastomers (Ginder 1996). Ferrofluids usually contain magnetic particles (smaller than 10 nm) and are said to have weak field dependent viscosity, since it typically increases by a factor of 2 in the presence of a magnetic field (Rosenweig, 1985 in ref. Ginder, 1996). Magnetorheological (MR) fluids are non-colloidal suspensions of micrometer-sized magnetizable particles supended in non-magnetic liquids. The larger particles of MR fluids (compared to ferrofluids) enables them to reversibly change from free flowing liquids to solids under the application of a magnetic field, and to be used in a number of applications. Magnetic powders are composed of magnetizable particles such as iron or some of its alloys. They can be used in clutches and rotary brakes; however these applications are always associated with high temperatures, which can eventually promote the failure of the particles due to oxidation (Ginder, 1996). These powders can also be used in image development in xerography. Magnetorheological elastomers are the solid-state analogues of MR fluids. They are obtained by suspending micrometer size magnetizable particles in a viscoelastic solid such as polymer gel or an elastomer. (Ginder, 1996; Ginder, et al 1999, Ginder, et al 2000; Carlson, 2000).

Electrorheological fluids are a class of materials that belong to the family of fluids whose properties depend on the applied electric field. Most of them are heterogeneous, comprising a dispersion of powders in insulating oils. Homogeneous ER fluids, such as liquid crystals, can also be used and have the great advantage of not being prompt to sedimentation.

ER and MR fluids share some common features. Both exhibit an increase of the apparent viscosity by several orders of magnitude when subjected to high fields (electric or magnetic, respectively) due to the formation of columnar structures in the direction of the field. In this paper we review the mechanisms, properties, composition of ER and MR fluids, and their applications mainly in fluid power systems.

## 2 Mechanism of MR and ER fluids

The magnetic particles of MR fluids have a large number of sub-domains inside themselves and each sub-domain has a randomly aligned dipole moment. The net dipole moment of a magnetic particle as a whole is very weak due to the random alignment of the dipole moments of the sub-domains. However, under

This manuscript was received on 10 November 2000 and was accepted after revision for publication on 2 July 2001

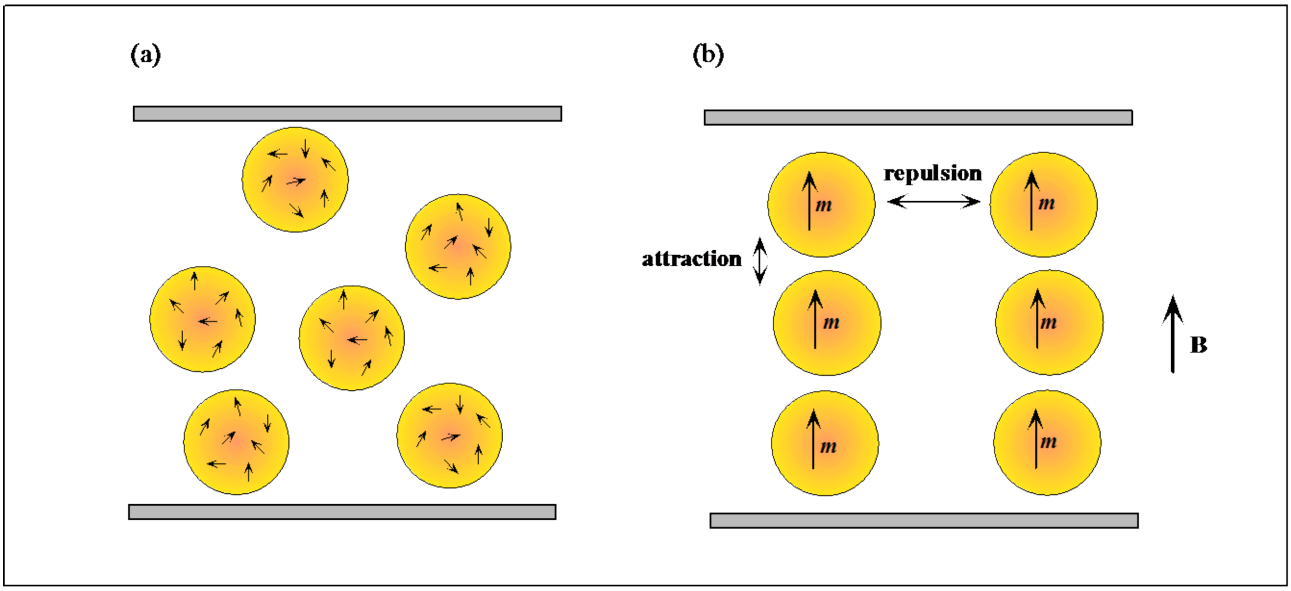


**Fig. 1:** *Magnetic interaction among particles of a MR fluid*

the influence of a magnetic field, all the sub-domains in a magnetic particle align in one direction and the magnetic dipole moment becomes considerable and such particles experience magnetic forces. The forces between two magnetic particles interact with each other and, based on the direction of these forces the particles attract or repel each other. As shown in Fig. 1, attraction happens in the direction of the magnetic field and repulsion, perpendicular to its direction. This phenomenon leads to the formation of a chain-like structure parallel to the field.

As explained above, the magnetorheological response of MR fluids results from the polarization induced in the suspended particles by the application of an external field (Jolly, et al 1998; Jolly and Nakano, 1998) which induces a dipole moment in each of them. As the dipole-dipole interaction between the particles increases and overcomes the thermal energy, the particles align to form chains along the field lines (Felt, et al 1996). A further increase in the magnetic field causes the aggregation of these chains into columnar structures, parallel to the applied field. These chain-like structures restrict the motion of the fluid, thereby increasing the viscous characteristics of the suspension. In this condition, these fluids show yield properties and their yield stress $\tau_y$ (minimum stress necessary to initiate flow) is a function of the applied field strength.

In a similar way, the particles of ER fluids polarize upon the application of an external electric field and electric dipoles appear. These dipoles attract head-to-tail in the direction of the electric field, forming the fibrous structures similar to what happens to MR fluids. The polarization in ER suspensions is commonly attributed to interfacial polarization, arising from permitivity and conductivity differences between the particles and continuous phase (Filisko, 1995; Rankin, et al 1998).

The behaviour of ER and MR fluids is most explained by the Bingham model, which states that for stresses below the yield stress (which is dependent on the field strength) there is no flow. In this case, the material behaves viscoelastically according to Eq. 1 and Fig. 2:

$$\tau = G\gamma \qquad (\tau < \tau_y) \tag{1}$$

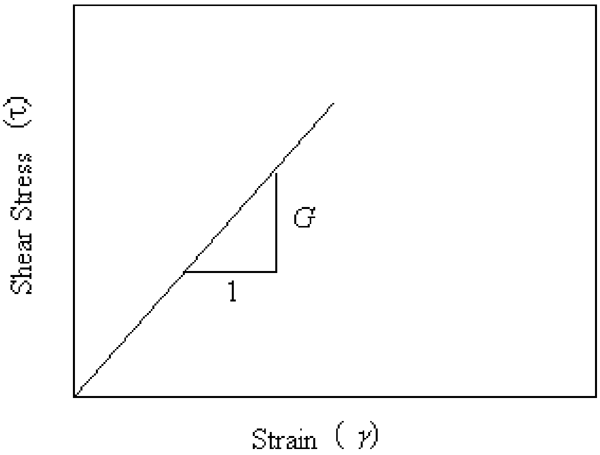


**Fig. 2:** *Typical behaviour of MR fluids in pre-yield region*

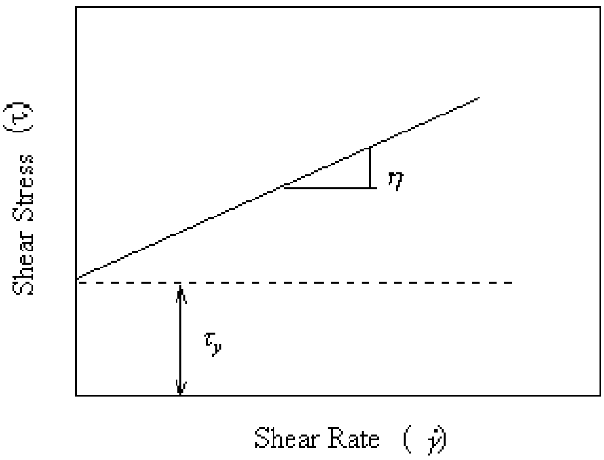

**Fig. 3:** *Typical behaviour of MR fluids in post-yield region*

However, for stresses higher than the yield stress, the flow is governed by the Bingham equation (see Fig. 3):

$$\tau = \tau_y + \eta \dot{\gamma} \qquad (\tau \geq \tau_y) \tag{2}$$

The magnetic field used for MR fluids can be generated by means of either a permanent magnet or an electromagnet driven by a low cost voltage supply.

## 3 Composition and Properties of MR and ER Fluids

### 3.1 MR Fluids

#### Materials

As discussed in the previous section, MR fluids are essentially non-colloidal suspensions consisted of a high concentration of magnetically polarizable particles (e.g. iron, ceramic ferrites, etc.)[1] in a non-magnetic medium (water, silicone oil, etc.). The behavioural differences among the fluids arise with changes on the particle concentration and magnetic nature of the particles.

The magnetorheological effect depends on the interparticle attraction, which, in turn, depends on the saturation magnetization of the particles, $J_s$ (Carlson and Jolly, 2000). Iron and its alloys are actively used as MR fluid particles, since their saturation magnetization is high. Iron has the highest value of saturation magnetization of known elements ($J_s$ = 2.1 T) while alloys of iron and cobalt have a slightly higher value: $J_s$ = 2.4 T. In spite of Fe-Co alloys lead to stronger MR fluids, their use may be limited to some applications due to their cost and relative unavailability. Some particles can be made of ceramic ferrites, however, their saturation magnetization is low (~ 0.4 - 0.6 T), and the corresponding maximum yield stress also tend to be small (up to 15 kPa). The complete saturation of a MR fluid is ($\Phi J_s$), where $\Phi$ is the volume fraction of the particles (Jolly and Nakano 1998).

As iron is a dense material, MR fluid particles tend to undergo sedimentation in the carrier fluid in the absence of a magnetic field. It is very important to prevent this sedimentation as it affects the overall performance of the MR fluid. Irreversible sedimentation or centrifugation is disastrous in practical applications and has been combated by several techniques. As the sedimentation rate is a quadratic function of the particle size, one approach to improve the stability of the MR fluid is to reduce its size. Reducing particle size also reduces the interparticle attractive forces. The key is to get an optimum size of particle that, in the absence of a magnetic field, will present a random Brownian motion able to prevent the sedimentation, and that will have enough interparticle attractive forces in its presence (Ginder, 1996).

The typical size of MR fluid particles ranges from 0.1 to 10 μm (one to three orders of magnitude larger than ferrofluid particles) (Phulé, et al 1999; Carlson and Jolly, 2000; Rankin, et al 1998), and the typical volume fractions tend to be about 0.3-0.5 (Phulé, 1998). Usually, higher volume fractions are not used since they can lead to an increase of the viscosity of MR fluids in the absence of a magnetic field. However, if a multimodal particle size distribution is used in the synthesis of MR fluids, the maximum possible volume fraction of the particles can be increased without causing an unacceptable increase in the "off-state" viscosity (Phulé, 1998).

There are some MR fluids (NMR) that, while very similar in structure to magnetorheological fluids, contain nano-sized magnetic particles, this being the essential difference between NMR and MR fluids (Korman, et al 1996). The particles in NMR fluids are so small that only single domain particles exist in the presence of a magnetic field, while particles of MR fluids have multi-domains[2]. For this reason, the magnetic field required for NMR fluids is comparatively much smaller. Moreover NMR fluids do not present problems of particle sedimentation and particle abrasiveness as MR fluids. The advantage of these fluids compared to ferrofluids is their higher yield stress obtained upon the application of a magnetic field. Besides this, NMR fluids are liquid and stable over a wide temperature range. In fact, storage for two weeks at 150°C under air does not deteriorate their performance significantly.

According to Korman et al (1996), the properties of NMR fluids are suitable for widespread industrial application. These fluids can somehow be classified between ferrofluids and MR fluids as they combine the benefits of both. While they have the smaller size of the former, they exhibit significant changes in the yield stress, sometimes even better than MR fluids.

Carrier fluids are chosen based on their rheological and tribological properties, temperature stability, cost, boiling point, corrosion and reactance with the particles and parts in contact, toxicity, overall stability and redispersibility (Phulé, 1998; Carlson, et al 2000). Some of the carrier fluids used more often are petroleum based oils, silicone based oils, mineral oils, polyesters, polyethers, water, synthetic hydrocarbon oils, etc. The preferred continuous phase for most MR fluids are organic liquids; however, for optical polishing applications, water is used as the base fluid due to the adsorption of organic liquids on optical surfaces.

For practical applications, MR fluids must be stable and redipersible. Without special additives, the particles of MR fluids settle out and form a very thick sediment. Once this happens, it is very difficult to redisperse the particles. Furthermore, if the MR fluid is composed of iron or ferrite particles, after the field is

[1] There are also some fluids made of polystyrene particles containing magnetic $Fe_2O_3$ grains (Felt, et al 1996).

[2] Single domain particles represent permanent magnetic dipoles and hence as a result require a very small externally applied magnetic field to align these particles.

applied, it is believed that a very small magnetization remains in the particles (approximately 1% of the saturation magnetization). This plays an important role in the agglomeration of the particles, mainly when they settle out because of the decrease of the average interparticle distances (Phulé, 1998).

Some additives such as xantham gum, silica gel stearates and carboxylic agents, can be added to magnetorheological fluids to make them thixotropic, preventing particle sedimentation (Carlson, et al 2000). When these agents are added to the MR fluid, they form a weak network that traps the MR fluid particles and prevent sedimentation at rest. Fine carbon fibers have also been used for this purpose. One disadvantage of adding such additives is the increase of the zero field viscosity of the MR fluid. Other additives can be used in order to reduce the corrosion of the particles.

### Basic Physical Properties

Typical MR fluids present yield stresses ranging from 50 to 100 kPa for applied magnetic fields of 150-250 kA/m (~ 2-3 kOe) (Carlson, et al 1996) and the ultimate strength is limited by the magnetic saturation. The temperature of operation is limited by the carrier liquid, and ranges from -40$^o$C to 150$^o$C. The density of MR fluids is 3-4 g/cm$^3$ (due to the dense particles) and their viscosity in the absence of a magnetic field is around 0.10 to 1.0 Pa·s at 25$^o$C (Carlson, et al 2000).

These fluids are not affected by most impurities and present response time in the order of milliseconds (Tang, et al 2000). The input power required by typical MR devices is 2-50 watts. Table 1 presents the properties of some commercial magnetorheological fluids.

### Lubricity and Compatibility

MF fluids are inherently somewhat abrasive. In devices such as wear bands and other bearing materials that are exposed to direct sliding contact with MR fluid, the abrasive properties of MR fluids are critical. The average coefficient of sliding friction for MR fluid lubricated iron-on-iron fluids conformal interfaces within MR fluid-based devices varies from 0.04 to 0.18[3] (Jolly, et al 1998). This represents a reduction of the sliding friction by a factor of two or three by using the MR fluid as lubricant instead of the dry surface.

In spite of the abrasiveness of MR fluids to be undesired in most of the cases, it can be very useful regarding polishing applications. Of late, many researches have been investigating this area (Kordonski and Jacobs, 1996-a; Jacobs, et al 1998; Kordonski and Golini, 1998; Umehara, et al 2000; Akagami, et al 2000, Kordonski and Golini, 2000).

Another important characteristic of MR fluids is their compatibility with materials within the device such as metals and seals. Table 1 shows a list of typical seal materials and the compatibility of MR fluids with them.

[3] These results were measured with an Instron (model 4204) using a standard sled geometry with contact dimensions of 7.6 cm by 7.6 cm, and they reflect the averages of multiple runs at a sled velocity of 2.6 mm/s with varying normal forces of 10 to 20 N in the absence of a magnetic field.

**Settling Characteristics**

There exists a density mismatch between the magnetic particles and the carrier agent in MR fluids resulting in settling. The degree of sedimentation depends on the particular application of the fluids. While sedimentation might be of major concern in a seismic damper where the active cycles of the damper are very few, it might not be that important in a brake application, in which the fluid is generally in motion (Jolly, et al 1998). In general, settling is governed by the rheological characteristics of the suspending medium, surface properties of the magnetic particles, and the presence of surface active agents. In addition to this, settling also can be influenced by remnant field, device orientation and by aspects of the geometry device. Data on sedimentation rates of some MR fluids are indicated in Table 1.

**Rheological Properties**

The rheological properties of MR fluids depend on the concentration, density of particles, particle size, shape distribution, properties of the carrier fluid, additional additives, applied field strength and temperature, among other factors.

In the absence of a magnetic field, MR fluids behave like a Newtonian fluid. However, in its presence, they exhibit a Non-Newtonian behaviour and typically show elastic properties before the yield phenomenon occurs. As the strain on the fluid increases, a transition from elastic to viscous behaviour takes place. A yield or critical strain characterizes this transition. Weiss et al (1994) inferred experimentally that the transition from elastic to plastic behaviour occurs at a strain value lower than 0.08%. This low yield strain value inhibits the use of MR fluids in applications such as adaptive structures that require stability in pre-yield properties. In the post-yield state the fluid generally exhibits viscous properties.

While the initiation of flow in the fluid is determined by the static yield stress (obtained by the Bingham model), the dynamic yield stress[4] and the plastic viscosity determine the behaviour of the fluid during flow. It was found that the dynamic yield stress varies linearly with the particle size and the volume fraction (for concentrations smaller than 15 vol%), and with the square of the magnetic field strength (Felt, et al 1996).

The loss angle $\delta$ ($= G''/G'$) of MR fluids indicates the relation between the viscous (loss modulus, $G''$) and elastic (storage modulus, $G'$) behaviour. Typically, it shows the phase difference between the strain wave (applied to the fluid) and the resulting stress wave (response generated within the fluid) in an oscillatory

[4] The value dynamic yield stress is obtained by extrapolating the shear stress curve to the point where the shear rate is zero.

**Table 1:** Some commercially available MR fluids

| MR Fluid / Properties | MRX-126PD | MRF-132LD | MRF-240BS | MRF-336AG | Iron based | Ferrite based |
|---|---|---|---|---|---|---|
| **Maker** | Lord Corp. | Lord Corp. | Lord Corp. | Lord Corp. | University of Pittsburgh | University of Pittsburgh |
| **Particles** | iron (~ 3 μm) | iron (~ 3 μm) | iron (~ 3 μm) | iron (~ 3 μm) | carbonyl iron (~ 5-7 μm) | nickel zinc ferrite (~ 2 μm) |
| **Carrier fluid** | Hydrocarbon oil | synthetic oil | water/glycol | silicone | organic liquids | organic liquids |
| **Density [g/cm$^3$]** | 2.66 | 3.055 | 3.818 | 3.446 | — | — |
| **Operating temperature** | -40$^o$C to 150$^o$C | -40$^o$C to 150$^o$C | -10$^o$C to 100$^o$C | -40$^o$C to 150$^o$C | — | — |
| **Concentration** | 26.0 % by vol. | 80.74 % by weigth | 83.54 % by weigth | 82.02 % by weigth | 30-40 % by vol. | 30-40 % by vol. |
| **Viscosity [Pa·s]** | — | 0.94 (at 10 s$^{-1}$) 0.33 (at 80 s$^{-1}$) | 13.6 (at 10 s$^{-1}$) 5.0 (at 50 s$^{-1}$) | 8.5 (at 10 s$^{-1}$) | — | — |
| **Yield stress [kPa] (@ 1 Tesla)** | — | — | — | — | ~ 100 kPa | ~ 100 kPa |
| **Compatibility** | compatible with nitrile rubber and fluoroelatomer. Poor compatibility with natural rubber. | not compatible with natural rubber or hydrocarbon based synthetic rubber formulations | not compatible with aluminum, not recommended for long term use with dynamic seals | compatible with natural rubber. Not recommended for long term use with dynamic seals | — | — |
| **open/closed system** | — | open or closed | closed | closed (recommended) | — | — |
| **Settling** | settles at 1.0 % per day | settles softly, and remixes with a 2-3 cycles of the device | settles softly, and remixes with a 2-3 cycles of the device | settles softly, and remixes with a 2-3 cycles of the device | — | — |
| **Applications** | — | multi-purpose, dampers, brakes, mounts | mounts, demo devices, toys | mounts, dampers | — | — |

Sources: Jolly, et al 1998; Jolly and Nakano, 1998; Phulé and Ginder, 1998; Phulé, 1999; Phulé, et al 1999; Carlson and Jolly, 2000 and www.mrfluid.com.

deformation. In the elastic regime, the fluid shows a very low value of loss angle, which increases as the viscosity increases. At pure viscous behaviour the material shows a very high value of the loss angle ($\delta$ = 90$^o$), indicating a large phase difference between the applied strain and the generated stress.

Felt et al (1996) studied a MR fluid made of an aqueous suspension of magnetizable polystyrene spheres. The polystyrene particles were coated with the surfactant sodium dodecyl sulphate, which stabilized the MR fluid against aggregation. The increase of the magnetic field strength and the volume fraction of the particles produced an increase of the apparent viscosity. The effect of the increase of the particle size was studied for lesser number of observations and a linear dependence of viscosity on particle size was observed.

Jiang et al 1998 reported that the increase of the shear rate produces an increase of the shear stress and that the static yield stress increases with the increase of particle size. This is explained by the fact that the strength of the magnetic dipole depends on the size of the particles. Increasing their size increases the dipole strength and the attractive forces among them, increasing the overall yield stress. However, for a fixed volume fraction, the total number of particles contained in the MR fluid reduces with the increasing particle size. This decreases the MR effect, which is not advisable. Hence for the best results, the increase of the particle size should be done only to a certain extent so that it will not harm the overall MR effect exhibited by the fluid.

Zhu et al (1998) studied the effects of different microstructures on the dynamic yield stress and hysteresis properties of the fluid, and found that the rheological properties depend on the microstructure formed in the fluid. They observed that, depending on how fast the magnetic field was applied to the fluid, the alignment of the chains and the microstructure had a different shape. If the magnetic field was slowly applied, the fluid formed a stable structure of separated columns. This structure showed many aggregates, each of them of a small size. However, if the field was applied at a high rate, the formation of a "bent-wall" structure could be observed. Further it was seen that, for small fields strengths, the rate of the application of the field was not that important. However, when the magnitude of the field was high and it was induced at a fast rate, the overall effect was much more pronounced. The authors proposed that high ramping rates produced strong dipole moments within magnetic particles, resulting in a quick interaction between dipoles, making the particles to trap immediately in their local minimum energy states and form a globally metastable structure. For this kind of microstructure any disturbance of the structure would result in an immediate change in the microstructure and the particles would realign in a more stable structure. This structure showed a lower dynamic yield stress than the one formed with a field applied gradually, which magnetic particles were already aligned in their minimum state of energy. Thus the authors concluded that column dominated structure under slow ramping of the magnetic field has higher dynamic yield stress than the "bent-wall" dominated structure formed under a fast ramping rate.

**Magnetic Properties**

A good understanding of the magnetic properties of MR fluids is very important since, in many cases, the fluid itself represents the largest magnetic reluctance within the magnetic circuit. The knowledge of the magnetic properties of MR fluids helps the better design of magnetic circuits. Jolly et al (1996) have conducted experiments and documented the magnetic induction curves for samples of MR fluids with varying percentages of iron. They concluded that, in general, the magnetic induction increases with the field strength until saturation of the fluid takes place. This occurs at an intrinsic induction of $\Phi J_s$, where $\Phi$ is the particle volume fraction and $J_s$ is the particle saturation magnetization. That is, a fluid with 30 % of iron particles would saturate at a $\Phi J_s = 0.3 \times 2.1 = 0.63$ T.

Other observation from the *B-H* curves shows that MR fluids initially exhibit linear magnetization till certain field strength. Beyond the linear regime, the fluids exhibit gradual saturation and finally become completely saturated. The curves presented by Jolly et al (1996) are based on the mathematical model they have come up. The experimental data does not completely match with the values they obtained and the reason for this was attributed to two factors: one accounts for the magnetic interactions other than adjacent particles in the chain of particles, which are formed in MR fluids on magnetization. The other factor takes into account the gaps between particles in a single chain.

## 3.2 ER Fluids

**Materials**

There are basically two types of ER fluids: conventional fluids, whose particles contain additives to make the fluid electrorheologically active, and dry fluids. In the first ones, the ER phenomenon is a consequence of an extrinsic component, most commonly adsorbed water (or alcohols or some other electrolyte) with various surfactants added and has nothing or little to do with the chemistry of the particles (Filisko, 1995). There are, of course, properties of the materials that are beneficial to produce better ER materials, such as particle porosity, high surface areas, and high affinity for water, but, in this case, the ER mechanisms are not related to the particle chemistry. The problem with this type of fluids is that the water severely limits their potential application, mainly due to:

- thermal runaway (heating caused by the Joule effect can drive off some water, increasing the current, which, in turn, will drive off more water, etc. until virtually all the water is off and the fluid no longer works)
- need of high power
- limited operating temperature range
- electrolysis
- corrosion of devices containing the fluid
- instability of the fluid
- irreproducibility of different batches
- solid mat formation, upon settling, due to interparticulate hydrate bond formation.

With the discovery of water free (dry) or intrinsic systems, many improvements were realized, most of them having to do specifically to the absence of water (Filisko, 1995):

- elimination or minimization of runaway, electrolysis and corrosion issues
- low currents ($10^3$ to $10^6$ lower as a result of dryness) and consequent decrease of power
- larger temperature range (zeolite operate from -60°C to 350°C when dispersed in silicone oil)
- improved instability and reproducibility
- substantially reduction of solid mat formation and settling.

Dry electrorheological fluids, which are intrinsic ER systems, can be classified as ionic conductors (e.g. aluminosilicates or zeolites), semiconductors (e.g. polyacene quinone radicals, polyaniline), polyelectrolytes (e.g. poly lithium methacrylate) and solutions (e.g. poly-γ-benzyl L glucamate in various solvents, poly (hexyl isocyanate) in various solvents) (Filisko, 1995).

When choosing the carrier fluid, it is important to select insulating oils with a density similar to that of the particles in order to minimize sedimentation. Obviously matching densities at all temperatures is impossible; however, it can be made in a certain range of working temperature. Additives are also part of the formulation of ER fluids to prevent flocculation, which increases sedimentation rates and makes difficult the redispersion by agitation (Block and Rattray, 1995). Table 2 shows typical components of ER fluids.

Many industrial and academic groups have used organic or polymeric materials as the particulate phase. By using synthetic chemical techniques, it is possible to adjust their dielectric properties to control the conductivity and dielectric constant of these materials (Rankin, et al 1998). Besides this advantage, these particles also have densities that nearly match that of the carrier fluid, and are non-abrasives.

**Table 3:** Some commercially available ER fluids (Jolly and Nakano, 1998)

| Controllable Fluid | Supplier | Particulate % (V/V) | Carrier Fluid | Density (g/ml) |
|---|---|---|---|---|
| TH-403 | Fujikura-Kasei Co | Polymer/inorganic (~15 μm), 35 % | Silicone oil | ~ 1.2 |
| TX-ER8 | Nippon Shokubai Co. | NSP (~5 μm), 40 % | Silicone oil | ~ 1.2 |
| TX-ER6 | Nippon Shokubai Co. | NSP (~5 μm), 20 % | Silicone oil | ~ 1.2 |
| Bridgestone ERF | Bridgestone Corp. | Carbonaceous (~3 μm), 33 % | Silicone oil | ~ 1.2 |
| Lubrizol ERF | Lubrizol | Doped poly(aniline) | — | ~ 1.2 |

**Table 4:** Specifications and performance data of commercially available ER fluids at 25°C (data obtained from Bridgeston/Firestone Research)

| Property | ERF BA-1 | ERF HP-1 | ERF HP-2 |
|---|---|---|---|
| **use** | Bridgestone's standard ERF | Bridgestone's high performance ERF suitable for many standard applications | Bridgestone's extreme performance ERF suitable for severe and demanding applications |
| **viscosity** | 0.09 Pa·s | 0.07 Pa·s | 0.15 Pa·s |
| **yield stress** | 1.0 kPa (3 kV/mm)<br>1.6 kPa (4 kV/mm) | 1.0 kPa (3 kV/mm) | 4.2 kPa (4 kV/mm) |
| **current density** | 13 μA/cm$^2$ (3 kV/mm)<br>33 μA/cm$^2$ (4 kV/mm) | 8 μA/cm$^2$ (3 kV/mm) | 14 μA/cm$^2$ (4 kV/mm) |

| | |
|---|---|
| **response time** | 2 ms (little variation over a wide temperature range) |
| **dispersion** | non-caking with minimal settling and easy re-dispersibility |
| **toxicity** | non-toxic |
| **compatibility** | no reactivity with common enineering materials (Ti, Al, SS, Delrina, Nylon, etc.) |

**Table 2:** Typical components for ER fluids (Gandhi and Thompson, 1992)

| Solute | Solvent | Additive |
|---|---|---|
| kerosene | silica | water and detergents |
| silicone oils | sodium carboxymethyl cellulose | water |
| olive oil | gelatine | none |
| mineral oil | aluminum dihydrogen | water |
| transformer oil | carbon | water |
| dibutyl sebacate | iron oxide | water and surfactant |
| mineral oil | lime | none |
| p-xylene | piezoceramic | water and glycerol oleates |
| silicone oil | copper phthalocyanine | none |
| transformer oil | starch | none |
| polychlorinated biphenyls | subphopropyl dextran | water and sorbitan |
| hydrocarbon oil | zeolite | none |

Carbonaceous particles are an example of this kind of material, and ER fluids that use them in their composition were developed at Bridgestone (Ishino, et al 1995). Bayer developed ER fluids with metal-salt-containing polyurethanes particles (Rankin, et al 1998). By adjusting the metal salt content and the polyurethane crosslink density enabled tailoring of the field-induced yield stress and current density of these fluids. Nippon Shokubai developed a water-activated fluid based on sulfonated polystyrene particles (Asako, et al 1995). By driving off the water that was not strongly associated with the polymer, the shear stress, current density and long-term stability were improved. Lubrizol and other researchers have been explored another class of polymers that include the polyanilines, which can be doped to control their conductivity and dielectric constant over a wide range (Havelka, 1995; Rankin, et al 1998). Tables 3 and 4 present some properties of commercial ER fluids.

Other researchers are studying coating of particles in order to improve the performance of ER fluids. Examples of these multilayer particles are silica core, a metallic layer and a titania top coating (Tam, et al 1997), and coated glass microbaloons with poly (vinyl alcohol) (Qi and Shaw, 1997).

Besides polymer particles, ER fluids also can be made of other materials. Inorganic particles, such as crystalline aluminosilicates, which exhibit the ER effect without the necessity of water, can be present in the composition of ER fluids (Rankin, et al 1998).

All the ER fluids discussed above can present particles settling and wear problems. The use of solutions of liquid crystals eliminates these problems, since they exhibit the ER effect, and form homogeneous liquid crystal phase and do not have particles in their composition. As an example, a solution of 26 t% by weight poly (hexylisocyanate) in xylene has shown a thirty-five fold increase in viscosity under 1.5 kV/mm when $\dot{\gamma}$ = 0.4 $s^{-1}$ (Block and Rattray, 1995). It is also of potential interest to study the MR effect of lyotropic liquid crystal systems since magnetic ordering can occur. Other homogeneous polymer blends, such as liquid crystalline polymers (LCPs) or polyurethane and dimethylsiloxane (DMS), are also been reported in the literature (Orihara, et al, 1998; Kito et al 1998; Kimura, et al 1998) and investigated by groups like Asahi Chemical (Inoue, et al 1998).

ER fluids that are sensitive to both electric and magnetic fields are called ERMR fluids and have been investigated by Takeda et al (1998), Fujita et al (1998) and Postrehhin and Zhou (1998).

### Properties

An ER fluid typically is a dispersion of particles of 1 to 100 μm in size. Most researchers find a volume fraction between 10 and 40 % to be the optimum particle loading for a practical balance between zero-field viscosity and dynamic yield stress (Havelka, 1995). When formulating an ER fluid using a particular material, a number of properties need to be optimized, as shown in Table 5.

**Table 5:** ER fluid requirements for a variety of applications (Havelka, 1995)

| ER Fluid Performance | Value |
|---|---|
| dynamic yield stress at 6 kV/mm | > 4 kPa |
| zero-field viscosity | < 100 cp |
| current density at 6 kV/mm (DC) | < 300 $mA/m^2$ |
| operating temperature range | -20 to 140$^o$C |
| response time | miliseconds |
| dispersion properties | stable |
| tribology properties | non-abrasive |
| environmental properties | non-toxic |

Lowering current density continues to be a challenge in both extrinsic and intrinsic ER fluids. In an attempt to reduce it, insulating coatings and surfactants have been investigated. Polysaccharide coatings on polyaniline dispersions demonstrated to reduce the current density and increase the shear stress values in steady state. For 5 % by weight of coating, the steady state shear stress (at 20$^o$ C) increased 68 % and the current density decreased 69 % (Havelka, 1995).

Based only on polarization, highly conducting particles, such as metals dispersed in an insulating oil, should provide optimum ER effect. However, this kind of dispersions is very conductive and does not provide fluids of significant shear stress. Researchers at Lubrizol felt that a very thin coating or oxide layer on the metal was needed to investigate bulk and surface polarization. However, even with the insulating coating, the metal particles demonstrated weak ER activity. The failure in making good ER substrates was an indication that there might exist an optimum level of conductivity in the semi-conducting region.

Since the particles of ER fluids tend to settle and many of the applications may promote settling through vibration or centrifugation of the fluid, dispersion stability is a challenging requirement. Many approaches (such as liquid systems, density matching, steric stabilization, electrostatic stabilization and additives that are shear-thinning) have been investigated to reduce settling and to improve redispersibility. Each of these approaches affects both the dispersion properties and ER properties, including yield stress, current density, zero-field viscosity (Havelka, 1995).

## 4 Advantages and Disadvantages of MR Fluids Compared to ER Fluids

Magnetorheological (MR) and electrorheological (ER) fluids have attracted the interests of many researchers in the entire world mainly due to two reasons:

- their properties can be easily controlled by a magnetic or an electric field, respectively;
- their ability to provide simple, quiet and rapid response interfaces between electronic controls and mechanical systems.

Although quite similar to each other in terms of the basic concept of application, ER and MR fluids do have differences between themselves. One of these differences is the way the field is generated: for ER fluids it is necessary a source that supplies high voltage at low current (which is very expensive), whereas in the case of MR fluids, the source needs to be able to supply high current at low voltage.

During the last five years, the interest on MR fluids has increased around 75 %[5], mainly because of their higher yield stress (50-100 kPa), which are able to generate greater damping forces when compared to ER fluids (3-5 kPa). The maximum strength of a given ER fluid is usually limited by its dielectric breakdown (Felt, et al 1996). On the other hand, the ultimate strength of a MR fluid is limited by its magnetic saturation capacity. Besides this, the working temperature range of MR fluids is very large and is more suitable for a wide range of industrial applications. These fluids can be easily used for a range of -40°C to +150°C (Dyke, et al 1996), whereas the temperature range for non-ionic ER fluids is from -25°C to +125°C (Carlson, et al 1996)[6]. Moreover, magnetorheological fluids are not as sensitive to impurities in the suspension as electrorheological fluids.

[5] This data is based on the papers presented on the International Conference on ER Fluids and MR Suspensions during the last five years (1995 - 2000).

[6] ER fluids polarized by ionic conduction can be typically used in the range of 10 to 90°C (Carlson, et al 1996).

In spite of the advantages listed above, MR fluids also present some disadvantages when compared to ER fluids. The relatively large particles coupled with their high specific weight results in big problems such as sedimentation. The magnetic particles in typical MR fluids settle out over a relatively short period of time (a few minutes to a few hours) (Phulé and Ginder, 1998). As most MR fluids also show poor redispersibility, once the particles settle out, they form a very tightly bound network that makes extremely difficult to "re-mix" the fluids (Phulé, et al 1999).

Moreover, the size and heating of the coils that generate the magnetic field has been a challenge for the MR technology. Carlson et al (1996) suggested that it is very difficult to estimate the difference between the Joule losses in MR and ER fluids. The loss in the ER fluid happens during the transmission of the current inside the fluid and depends on the fluid properties such as temperature and composition. On the other side, in a MR fluid, the losses happen in the coil used to produce the magnetic field and depend on the coil geometry, material, etc.

The input power of ER and MR fluids is usually around 10 watts. However, the input power for ER fluids can be dramatically reduced when they are used in microdevices, reaching levels much lower than those for magnetorheological fluids. This is a great advantage of ER fluids over MR fluids. Table 6 compares some properties of typical ER and MR fluids.

As extensive research has been undertaken in the field of electrorheology, a large variety of ER fluids are commercially available, whereas MR fluids are very costly and there are only few suppliers.

These advantages of ER over MR fluids associated with the facility to obtain a homogeneous electric field are some of the reasons for 63 %[7] of the researchers to continue investigating about ER technology instead of changing to magnetorheology.

Recently a new way of using MR fluids has been developed. Basically it consists of devices containing a MR fluid that is constrained by capillary action in an absorbent matrix such as sponge, open celled foam or felt. MR fluid sponges can be used in controllable linear dampers, rotary brakes and disk brakes.

Some salient features of these devices are (Carlson, 2000):

- low cost
- no susceptibility to gravitational settling
- the absorbent matrix requires only a low volume of MR fluid and the device is operated in direct shear mode without the need of seals, bearing volume compensators or precision mechanical tolerances
- multi-degree of freedom devices can be constructed
- long life, as the wear of the sponge is little.

## 5 Structure Formation

In this section we will discuss the type of structure formed in ER/MR fluids under the application of an applied field and shear flow. This study helps us to better understand the ER/MR phenomenon in the various kinds of flow.

### 5.1 Chain Breakage and Reformation Model

It is generally accepted that the fibrous structure of ER and MR fluids (subject to a field and shear flow), resists to shear stress until its elastic limit is attained ($\tau = \tau_y$). After that, it breaks, indicating that the shear stress disturbs the formation of the chains and decreases the ER/MR effect (as shown in Fig. 4).

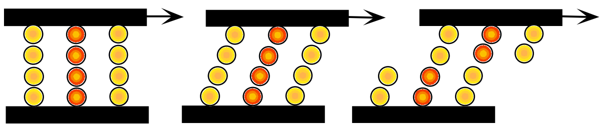

**Fig. 4:** *Chains breakage and reformation of MR fluids*

**Table 6:** Comparison of properties of typical ER and MR fluids

| Property | ER Fluids | MR Fluids |
|---|---|---|
| yield stress (field) | 2–5 kPa (3-5 kV/mm)<br>field limited by breakdown (Carlson, 1996) | 50–100 kPa (150-250 kA/m)<br>field limited by saturation (Carlson, 1996) |
| operating temperature | +10 to + 90 $^o$C (DC) (ionic) - (Carlson, 1996)<br>-25 to +125 (AC) (non-ionic) - (Carlson, 1996) | -40 to +150 $^o$C (Carlson, 1996)<br>(limited by carrier fluid) |
| specific gravity | 1 – 2.5 (Carlson, 1996) | 3 – 4 (Carlson, 1996) |
| sensitivity to contaminants | yes | no |
| viscosity (no field) | 0.2 - 0.3 Pa·s at 25$^o$C (Carlson, 1996) | 0.2 - 0.3 Pa·s at 25$^o$C (Carlson, 1996) |
| current density | 2-15 mA/cm$^2$ (4 kV/mm, 25$^o$C) - (Carlson, 1996)<br>carbonaceous ERF: 25 μA/cm$^2$ (3.5 kV/mm, 25$^o$C) - (Ishino, et al 1995) | can be energized with permanent magnets (Carlson, 1996) |
| input power | ~ 10 watts[7] | ~ 10 watts |
| ancillary materials | Any conductive surface (Carlson, 1996) | iron/steel (Carlson, 1996) |
| price of commercial fluids | ~ US$ 500/l to US$,750/l | ~ US$ 600/l |

[7] This value is estimated for $E$ = 4 kV/mm, $j$ = 25 μA/cm² and $A$ = 100 cm². However, it can be dramatically reduced for microdevices.

This model tries to explain changes observed on the shear stress of ER/MR fluids in different types of flow mode. However, if an ER or a MR fluid is sheared with constant shear rate, the result can be different and the shear stress, or the fluid viscosity, can increase with time. This behaviour was analyzed by some authors (Vieira, et al 2000; Filisko and Henley, 2000; Henley and Filisko, 1999) in terms of changes on the micro-structure, and a new model was proposed to complement the chain breakage and reformation model, as shown in the following.

### 5.2 Lamellae Formation Model

A lot of research work has been done in order to obtain ER fluids with high values of yield stress. However, these efforts did not bring an improvement of the performance of ER fluids (Filisko, et al 1998). In this way, Filisko and Henley (1999, 2000) proposed that the chain breakage and reformation does happen; however, it may not be the primary effect occurring in ER fluids. They proposed that the chains/columns under field and flow align themselves in tight packed geometric structures consistent with the field. In this model, slip planes develop, not perpendicular to the columns, but parallel to them. In this way, the shear dissipation occurs not by chains breaking, but by these structures maintaining their integrity and shearing with respect to each other. That is, the chains would be randomly adhered to one of the electrodes and the relevant slip planes would be parallel to the column directions and not normal to them, as it would occur if chains were breaking.

Vieira et al (1999, 2000) studied changes on the ER structure in steady shear flow mode during long periods of time and in oscillatory shear flow mode. These modes are shown in the next two sections. These results can be extended to magnetorheological fluids as well, since they have a similar behaviour.

### 5.3 Structure Developed in Different Flow Modes

#### Steady Shear Flow Mode

The flow mechanism of fluids in shear flow mode is important regarding applications such as clutches, where the fluids are subjected to high shear rates for long periods of time.

Vieira et al (2000) carried out a series of experiments to study the effects of the shearing time, electric field strength and shearing rate on the shear stress. They conducted the experiments with three different types of ER fluids and studied the variation of these parameters experimentally. It was observed that when an electric field and shear flow were simultaneously applied to a sample of ER fluid, initially the fluid showed an increase of the shear stress, reached a maximum, started to decrease, and after some time, stabilized at a given value. In other cases, the shear stress initially increased until a constant value was attained. These changes in the shear stress behaviour were directly attributed to changes on the ER microstructure of the fluid.

To exactly determine these changes in the structure, solidified samples of the ER fluid were taken at various periods of time and a picture of them was taken, as shown in Fig. 5. When the fluid was subjected only to an electric field, chain-like structures were formed randomly in parallel to the field. However, if it was then subjected to a shear flow, the structure became also orientated in the direction of the flow, and the microstructure formed circular concentric rings of ER particles with a gap between two adjacent rings. The thickness of the rings was said to be a complex function of the shear rate, particle concentration, applied electric field and shearing time.

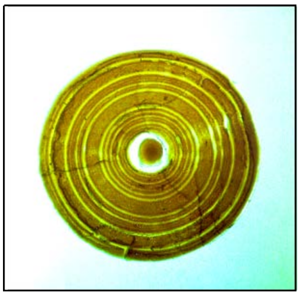

**Fig. 5:** *Flow pattern observed for an ER fluid sheared during 15 min between rotating discs at 100 $s^{-1}$ (E = 2 kV/mm) – (Vieira, et al 2000)*

The initial increase in the shear stress was attributed to changes in the orientation of the circular rings and the increase in their thickness. After some time had passed, the decrease in the shear rate was attributed to the decrease of friction between adjacent slip planes. Furthermore, with the increase of the shear rate, the number and thickness of the rings increased. This explains the overall increase of the shear stress. The increase of the electric field strength produced an increase of the thickness of the rings and, as a result, the shear stress of the material increased.

Tang et al (1998) obtained a similar pattern for an ER clutch (working for few seconds) and stated that as the shear strain increased with time, the columnar structures were broken by shear and reformed under the electrostatic interaction. During the breaking-reforming process, the layer structures formed and reached an equilibrium state, which depended on the electric field strength and on the shear rate.

Volkova et al (1999, 2000) studied the behaviour of an aqueous magnetorheological suspension of polystyrene particles (~ 0.48 μm) containing inclusions of magnetite (63 % by weight) in a steady shear flow. The experiments were carried out on a transparent cone-plate device mounted on a constant stress rheometer, and they observed the changes on the structure as the shear stress-shear rate curve was being built. For shear rates greater than 60 $s^{-1}$, the authors observed a layered structure with a typical period of 100 μm.

#### Oscillatory Flow Mode

Vieira et al (1999) have studied the behaviour pattern of ER fluids under oscillatory motion. The ER fluid was allowed to flow in an oscillatory manner through a slit channel while an electric field was simultaneously applied. The microstructure of the ER fluid was observed by means of an optical microscope taking side and top view images of the flow structure. The top view is shown in Fig. 6.

By visualizing the ER microstructure, the authors observed three distinct regions within the slit channel:

- region A, composed of a high concentration of fixed fibers near the side wall which provided resistance to the flow motion
- region B, almost free of fibers and characterized by the passage for the ER fluid flow
- region C, with a high concentration of fibers and clusters that broke when the ER fluid flowed through the ER channel.

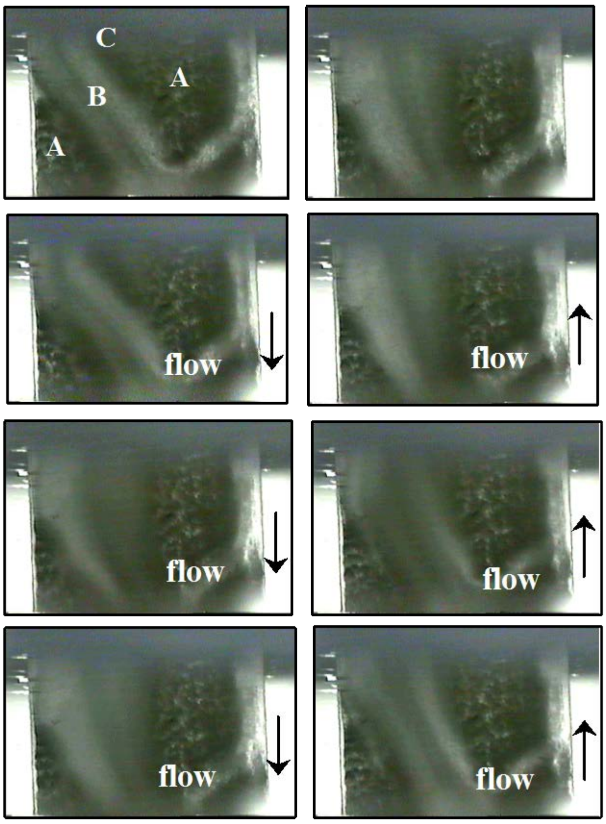


**Fig. 6:** *Visualization of the microstructure of the ER fluid at 1 kV/mm (f = 2.5 Hz, $\varepsilon_0$ = 460 %) – (Vieira, et al 1999)*

Thus, on the contrary of the expectancy, the main phenomena within the ER channel were not only the breakage of the fibers, but also the blockage of a part of the ER channel by the fixed fibers. The blockage area composed of the fixed fibers and its position were changed to give passages to the ER fluid, decreasing the resistance to its flow. The region B composed of parallel alignments of clusters was usually obtained for low values of electric field strength, and high values of strain amplitude and oscillation frequency.

Volkova et al (1999) observed the structure of a MR fluid in an alternating shear flow and found that, if the magnetic energy was high enough compared to the thermal energy, a phase separation took place and chains were formed in the direction of the field. However, for $\gamma > 0.15$, these chains rearranged in a periodic layered pattern similar to the region B observed by Vieira et al (1999) for the case of ER fluid subjected to 0.5 kV/mm ($f$ = 2.5 Hz, $\varepsilon_0$ = 460 %).

**Valve Mode**

Tang et al (1998) studied an ER fluid flowing through a slit channel and found two distinct stages for the structure formation of the ER flow in the ER valve. The initial stage occurred when the ER flow just entered within the electrodes, and the second one (called the post-saturation stage) occurred after the ER fluid had filled up the valve and the accumulation of particles reached a saturation level.

In the first stage, as the polarized particles aligned themselves in the direction of the field, the ER flow was being driven by a pressure gradient that tended to shatter the columnar-like structure. In the second stage, they noticed that the valve space was divided into a rest "bank" region and a flowing "river" region.

The non-uniform flow observed in the second case makes theoretical analysis difficult to be performed. In general, scientists use a continuous medium fluid mechanics approximation to simulate the behaviour of the ER fluid in this kind flow mode. However, the authors argued that in this case, two important facts should be considered: the increase of volume fraction within the ER valve and the narrowing of its width due to the existence of the ER "river".

## 6 Applications of ER and MR Fluids in Fluid Power Systems

The increasing interest and research on ER and MR fluids have led to newer fields of applications. The ability of ER and MR fluids to change viscosity in the presence of an electric or magnetic field and their high performance, makes them advantageous in interfacing electric signals and fluid power without the need of mechanical moving parts such as servo valves, dampers, clutches, etc. (Kondoh, et al 1995; Kondoh and Yokota, 2000-a and 2000-b). In this way, fluid power systems can benefit from the use of such a simple mechanism.

Research on fluid power using ER and MR fluids is being conducted at the Tokyo Institute of Technology (Kondoh and Yokota, 1999-a; Kondoh and Yokota, 2000-a; Yokota, et al 1999). Some of the studies focus on micromachines that use fluid power of high output power density to implement utility micromachines such as inspection robots for nuclear reactor small-diameter tubes. For this, it is necessary high performance micro control valves. ER and MR valves are being studied to be used in this application (Yokota and Yoshida, 2001). Investigations are also being carried out at the Institute of Fluid Power Transmission and Control (IFAS) in Aachen, in order to demonstrate possible uses of electrorheological fluids in hydraulic systems (Fees, 2001).

Other works on fluid power using functional fluids are reported in the literature: ER valves and actuators were studied by H. T. Strandrud, A. J. Simmonds, Kondoh and Yokota (1999-a), Choi (Choi, et al 1997, 1999, 2000-b), Wendt and Büsing (1998), Tanaka et al (1998), among others. Besides the works and researchers mentioned previously, there are other studies that have been done in the area of fluid power. Some of them are presented in the following sections. Though some active dampers use ER/MR valves as their components, the required performance environments for active dampers are either transient or oscillatory in nature. Hence, the use of these valves is different from their use in fluid control systems (Yokota, et al 1999), and these applications are discussed in Section 8.

### 6.1 Valves and Actuators

This section presents past research on applications of ER/MR fluids to fluid power systems.

ER fluids enable the design of miniaturized actuators, and even the disadvantage of high voltage requirements is improved since typical plate separations are below 100 μm (Kohl, et al 1998). Nevertheless, not too many works have been published on ER microactuators. One of the reasons for that is the lack of appropriate fluids that exhibit the ER (or MR) effect in narrow flow channels. Homogeneous ER fluids are promising candidates for microactuator applications due to the absence of sedimentation and abrasion (Kohl, et al 1998; Kondoh and Yokota, 1999-a; Kondoh and Yokota, 2000-a; Narumi, et al 2000).

Kohl et al (Kohl, et al 1998; Kohl, 2000) investigated the use of homogeneous ER fluids in microdevices with planar geometry. They found that the viscosity could be controlled within a factor of 25 using voltages below 500 V (Fig. 7), and that decreasing the gap up to 50 μm, no impact on the ER effect was verified. The authors then combined two ER microdevices to a pressure control actuator with one control port, as shown in Fig. 8. For zero voltage and a given pressure difference $\Delta P = (P_1 - P_0)$, the flow through the microdevice resulted in a pressure $P_c = (P_1 + P_0) / 2$. By increasing the voltage $U_1$, a decrease of $P_c$ occurred; in the same way, increasing $U_2$ produced an increase of $P_c$. Thus, an appropriate choice of $U_1$, and $U_2$ allowed an adjustment of $P_c$ between $P_0$ and $P_1$. The results showed that pressure differences $(P_1 - P_0)$ of 0.2 MPa could be controlled within 50 ms switching time by applying voltages between 400 and 500 V (Fig. 9). Then, the authors built an actuator for pressure control of fluidic microdevices with two ports by combining four capacitor elements to a fluidic bridge. By controlling the motion of a micropiston ($0.45\times1\times0.25$ mm$^3$) in the fluidic linear actuator, and for a given maximum pressure difference of 0.2 MPa, they obtained a maximum actuation force of 22 mN and strokes of 1 mm. These results open up interesting MEMS applications.

The use of micro ER valves has also been suggested by Kondoh and Yokota (1996, 1997-a, 1997-b, 1997-c, 2000-b). There are two types of micro ER valves: electrode-electrode type and orifice-electrode type, as shown in Fig. 10. The electrode-electrode type consists of two pairs of electrodes connected in series. Under a

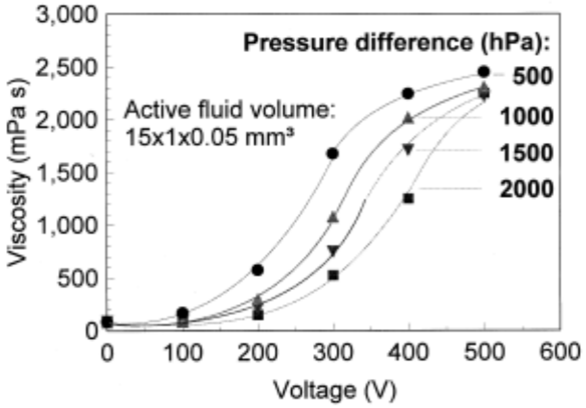


**Fig. 7:** *Dynamic viscosity-voltage characteristics for different pressure differences determined at room temperature (Kohl, et al 1998)*

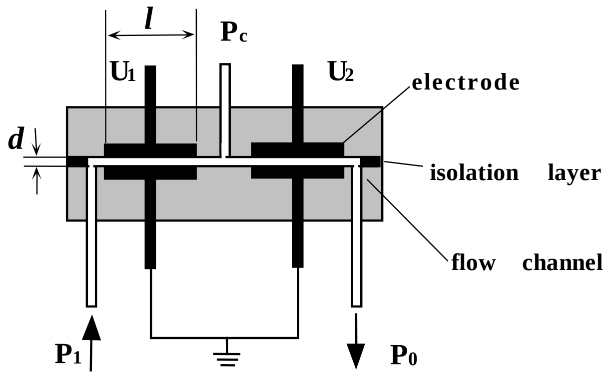


**Fig. 8:** *Schematic of an ER test device with planar design (Kohl, et al 1998)*

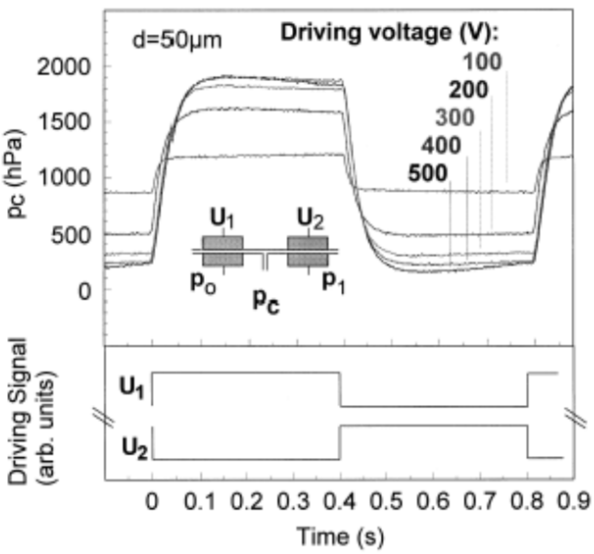


**Fig. 9:** *Time-dependent signals of a pressure control actuator at the control port for different voltages and a pressure difference ($P_1$ - $P_0$) of 0.2 MPa. The driving signals at the capacitor elements are indicated (Kohl, 2000)*

constant pressure supply, the ER fluid flows through the ER valves. A control port, in which a hydraulic actuator can be installed, is located between the upstream and downstream electrodes. The pressure of the control port goes up when the electric field in downstream electrode is stronger than that in upstream electrode, and vice-versa. The orifice-electrode type ER valve consists of a fixed orifice and a pair of electrodes, which are connected in series. The load pressure goes up when an electric field is applied in the electrodes. Comparing these two types of valves, the electrode-electrode type has a wider working range and should be employed as three-port ER valves (see Fig. 11) (Kondoh and Yokota, 1997-c).

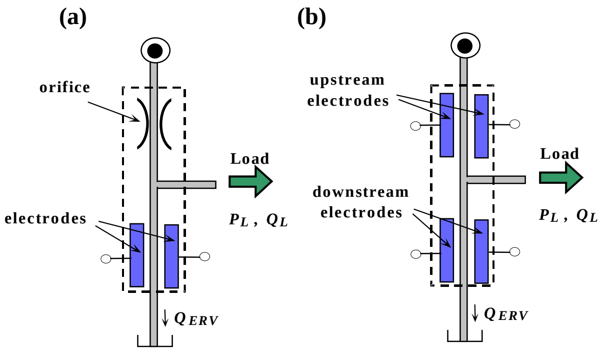


**Fig. 10:** *Configuration of the micro ER valve: (a) orifice-electrode type; (b) electrode-electrode type (Kondoh and Yokota, 1997-c)*

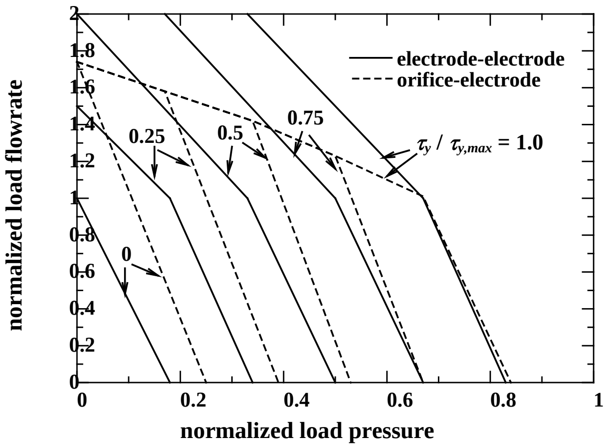


**Fig. 11:** *Static characteristics between normalized load flowrate ($Q_L/Q_{L,max}$) and normalized load pressure ($P_L/P_S$) for $P_S$ = 1.5(2L/H)$\tau_{y,max}$ – (Kondoh and Yokota, 1997-c)*

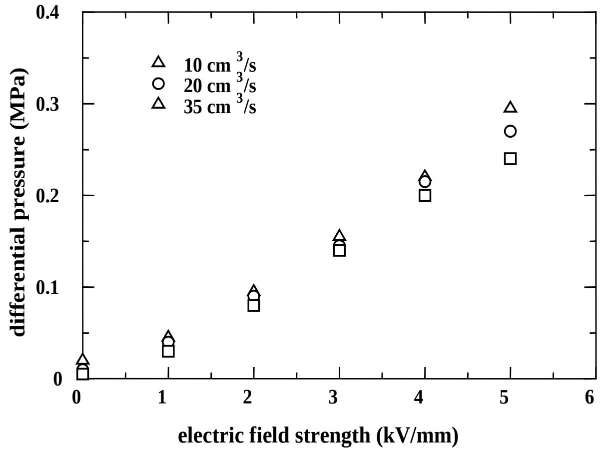


**Fig. 12:** *Static characteristics between differential pressure and electric field strength (data from Kondoh and Yokota, 1996)*

Kondoh and Yokota (1996) and Kondoh et al (1995, 1996, 1997) verified the static characteristics of a two-port ER valve. The manufactured valve was composed of twelve parallel plate electrodes with the dimensions: width = 25 mm, length = 40 mm, and gap = 0.5 mm. The static tests showed a linear characteristic between the differential pressure and the electric field strength with a little dependence on the flow rate (see Fig. 12), caused by the Bingham behaviour of the fluid. This is an advantage to fluid flow control. However, as the electric field increased up to 5 kV/mm, the loop area in the differential pressure - flow rate curve was found to increase, which is a disadvantage. Even though this happened, considering that the differential pressure was independent of flow rate through ER valves, an ideal pressure control valves could be realized for fluid power system.

After that they fabricated a three-port pressure control valve, whose maximum flow rate produced 0.7 MPa at 3 kV/mm in static experiments. The dynamic characteristics showed that the valve had a bandwidth of 30 Hz, which is adequate to be employed in servo systems. The authors applied the pressure control valve to drive a one-link manipulator with a flexible hydraulic actuator (FHA), which contracted in the axial direction with an increase of the internal pressure (see Fig. 13). The output force in the axial direction measured 230 N (maximum) at an internal pressure of 0.7 MPa, and the one-link manipulator was driven by the FHA whose arm inertial was 7.1×10$^{-3}$ kgm$^2$. The direct motion of the FHA was converted to the rotating motion of the arm using a rack and pinion. The calculated maximum torque was 2.3 N·m. Initially, the one-link manipulator was driven without feedback, which showed that the ER pressure control valve could, to some extent, drive the FHA. After that, a PI controller was employed as the servo control method. In this case, no steady error was detected and the rise time was 0.3 s (Fig. 14). The effectiveness of the valve was experimentally demonstrated for use in servo systems.

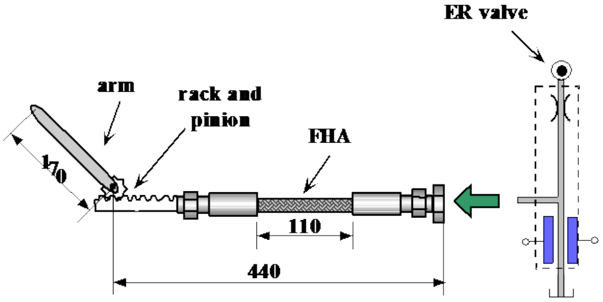

**Fig. 13:** *Schematicsof the one-link manipulator by making use of Flexible Hydraulic Actuator (Kondoh and Yokota, 1996)*

In a similar work, Kondoh and Yokota (1997-c) controlled a one-link manipulator driven with a small-sized rubber muscle-type actuator by using an electrode-electrode valve. The output force in the axial direction indicated 70 N (maximum) and the maximum torque of the arm was 0.3 N·m at an internal pressure of 0.6 MPa. The proposed micro three-port ER valve had a dynamic range of 0.35 MPa in the load pressure.

Kondoh and Yokota (1996, 1997-a, 1997-b, 1997-c, 2000-b), and Kondoh et al (1996, 1997) built and studied the behaviour of micro ER valves of different sizes. They calculated the dimensions of the ER valve using equations (A-2) and (A-3) included in the Appendix. One of these micro ER valves was designed to have performance indices of ($P_{L,max}$ - $P_{L,min}$) = 0.35 MPa and $Q_{L,min}$ = 0.02 $cm^3/s$. The electrodes were built in a comb-like shape where the inside part was connected to a high voltage supply and the outside part was grounded. It was found that this valve was able to control 0.25 MPa of a dynamic range in load pressure. Moreover, a minimum electric power was consumed when the electric field applied to both electrodes was the same, and equal to 2.5 kV/mm (Kondoh and Yokota, 1997-b). In this case, 68.75 % of power could be saved. Another micro ER valve, with dimensions $L$ = 46 mm, $W$ = 6 mm and $H$ = 0.3 mm (($P_{L,max}$ - $P_{L,min}$) = 0.4 MPa and $Q_{L,min}$ = 0.6 $cm^3/s$) was able to control 0.3 MPa of a dynamic range in load pressure (Kondoh and Yokota, 1997-a).

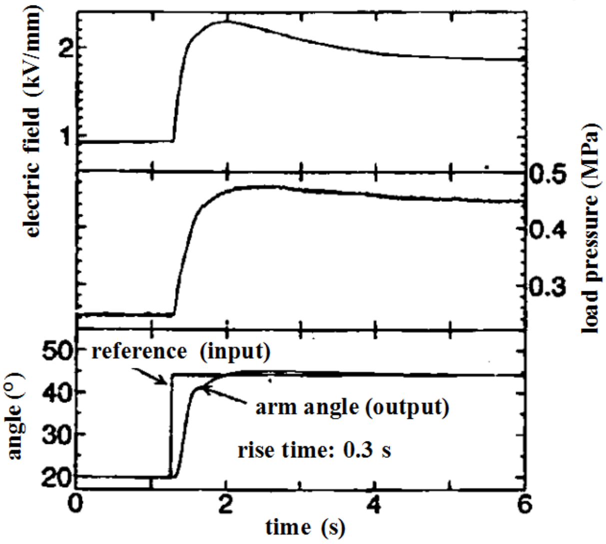


**Fig. 14:** *Step response of the one-link manipulator (with PI control) – (Kondoh, et al 1997)*

Wolff-Jesse and Fees (1998) studied the influence of the gap geometry on the ER effect in the flow mode. This study is very important, since, for manufacturing ER and MR resistors to control pressure and volume flow, it is necessary to know the influence of the relevant geometric data. They made experiments with different gap lengths (60, 80, 100 and 120 mm) and found that it has negligible influence on the ER effect per unit length. However, changing the gap width strongly influenced the electrorheological effect. As an example, for a flow rate of 6 l/min and 0.5 mm of gap width, the control rate $S$ was 1.89 (see Table 7). However, for a gap of 1 mm (100 % wider), $S$ = 8.15 (330 % higher). The authors also compared the data with theoretical models: Bingham and Herschel Bulkley. The results showed that the yield stress cannot be studied without taking in account the geometrical configuration data, and therefore cannot be considered a genuine substance characteristic. Instead, the yield stress was shown to depend on the field intensity, on the gap width and on the gap length. In addition, for the Bingham model, a dependency on the median gap velocity was discovered.

Other researchers have also studied the influence of the gap geometry on the ER/MR effect. With the recent progress of machine size reduction and micro-machine development, the application of ER and MR fluids to micro devices with very narrow gaps has become interesting. Narumi et al (2000) studied the ER effect in minute channels with parallel and non-parallel gaps of sub-millimeter size. They used 3 different configurations of gap (Fig. 15):

- channel P, composed of parallel electrodes,
- channel CD, a non-parallel channel with inclination of 5-20 degrees, through which the flow of the ER fluid could be convergent or divergent, depending on the direction of the flow,
- channel B, a converging part followed by a diverging one, with the same inclination.

**Table 7:** Control ratio for different gap widths ($Q$ = 6 l/min) – $\Delta P_0$ = pressure difference for $E$ = 0; $\Delta P_T$ = total pressure difference ($E \neq 0$); $\Delta P_e = \Delta P_T - \Delta P_0$.

| gap width (mm) | $\Delta P_0$ (bar) | $\Delta P_T$ (bar) | $\Delta P_e$ (bar) | $S = \Delta P_e/\Delta P_0$ |
|---|---|---|---|---|
| 0.5 | 5.7 | 15.7 | 10.8 | 1.89 |
| 0.75 | 1.8 | 10.7 | 8.9 | 4.92 |
| 1.0 | 0.83 | 7.6 | 6.8 | 8.15 |

Data obtained from table 2 and figure 6 in reference (Wolff and Fees, 1998)

They found that ER fluids are helpful for the flow rate control in a narrow gap if its size is about 10 times larger than the particle diameter. Comparing the converging and diverging flow in channel CD (Fig. 15), they observed a larger reduction of the flow rate for the converging channel, in the lower region pressure, upon the application of the electric field (see Fig. 16). For a pressure of about 0.03 MPa, the flow rate decreased from $4\times10^{-2}$ to about $1.5\times10^{-2}$ cm$^3$/s, almost 63 %. According to the authors, in the case of converging channel, weak clusters were generated at the lower electric field in upstream region and then grew up with the multiplier effect of the converging motion of clusters and the increasing electric field along the flow direction. On the contrary, the rapid formation of the cluster at the abrupt contraction before the diverging channel might be unstable, and the diverging flow associated with decreasing field might not be helpful for the ER effect. From their studies they concluded that the converging channel generated larger and more stable ER effect than the parallel and the diverging channels. An ER effect similar to the converging channel was obtained for the channel B.

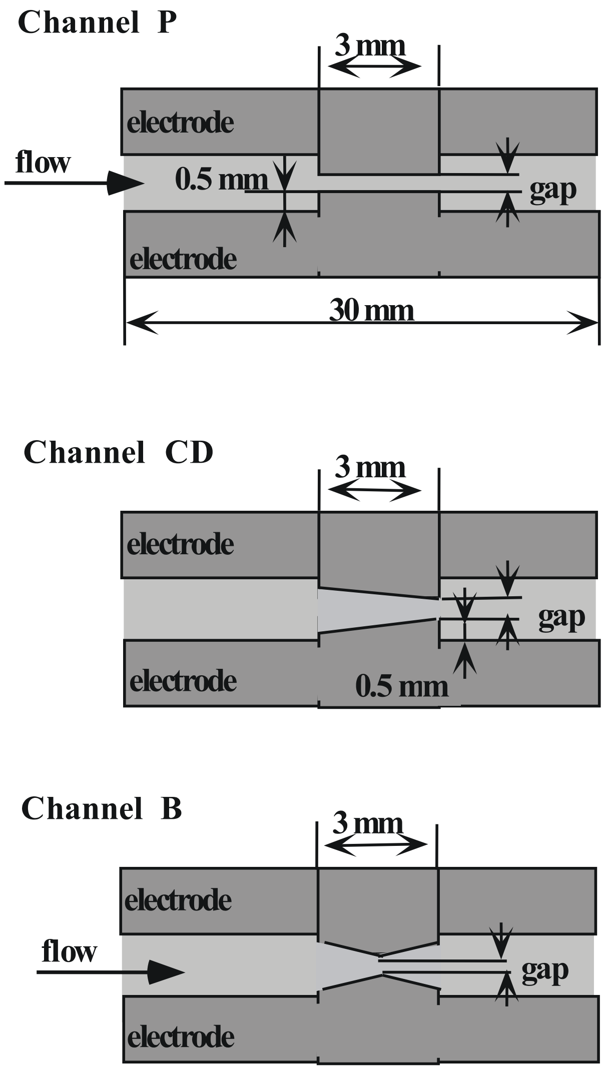


**Fig. 15:** *Side view of ER channels used by Narumi et al (2000)*

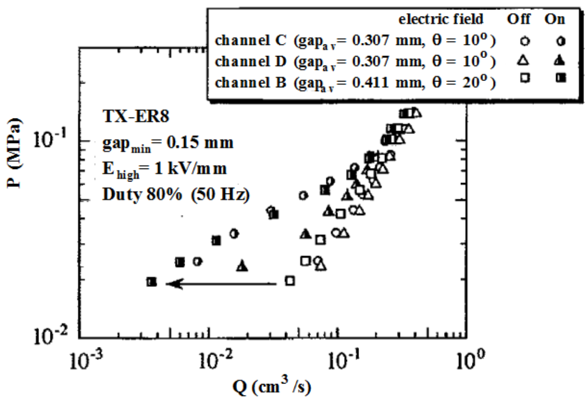


**Fig. 16:** *Flow characteristics in non-parallel channels under a rectangular pulse wave electric field (Narumi, et al 2000)*

Recently, practical and powerful micromachines such as micro maintenance robots for inside wall of small diameter pipes of power plants have been demanded and investigated. Kondoh and Yokota (1997-b, 2000-b) proposed and fabricated a in-pipe mobile machine weighting only 2.5 g with outer diameter of ϕ 9.8 mm and length of 34.5 mm. Three micro ER valves and three pairs of bellows-type actuators were installed in the micromachine. As it is known, bellows-type actuators can expand or contract depending on the internal pressure, which, in this case, was controlled by the micro ER valves. The three micro valves were connected in parallel to a power source and each valve could control independently each bellows-type actuator. Fig. 17 shows the mobile sequence of inchworm style. By repeating the sequence, the micro machine could mode step by step like an inchworm. It was observed that the average velocity of the micro machine increased according to the switching time for a range up to 0.06 s. However, the opposite happened when the switching range exceeded 0.06 s (Kondoh and Yokota, 1997-b), indicating the existence of an optimum value of switching time ($t_{SW}$). Particularly, for $t_{SW}$ = 0.5 s, the displacement was found to be around 1.75 mm (after 15 s). However, for $t_{SW}$ = 0.06 s, the displacement was almost 9 mm after 11 s (Kondoh and Yokota, 2000-b). Moreover, for $t_{SW}$ = 0.02 s, the average velocity decreased comparing to that for $t_{SW}$ = 0.04 s and the traveling of the micro-machine was unstable due to the decrease of the clamp force (Kondoh and Yokota, 1997-b). The authors plotted the average velocity as a function of the switching time (Fig. 18), and observed that the average velocity was proportional to the inverse of the switching time for $t_{SW} \geq 0.06$ s. They also observed that, for $t_{SW}$ = 0.06 s, the average velocity decreased in proportion to the load, and that the micro-machine could not travel with load exceeding 0.07 N.

When ER fluids are used in micro valves, some serious problems might happen, such as jamming and choking at the check valves in the resonantly driven piezoelectric micropump (Yoshida, et al 2001). Homogeneous ER fluids (like nematic liquid crystals) have been suggested as a solution in micro flow channels since they have no particles in them. This is an advantage when miniaturization of devices is desired (Park, et al 1999).

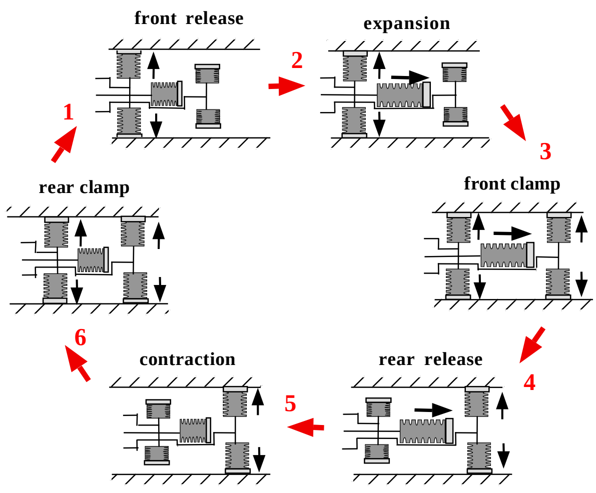


**Fig. 17:** *Mobile sequence of a micro in-pipe mobile machine (Kondoh and Yokota, 2000-b)*

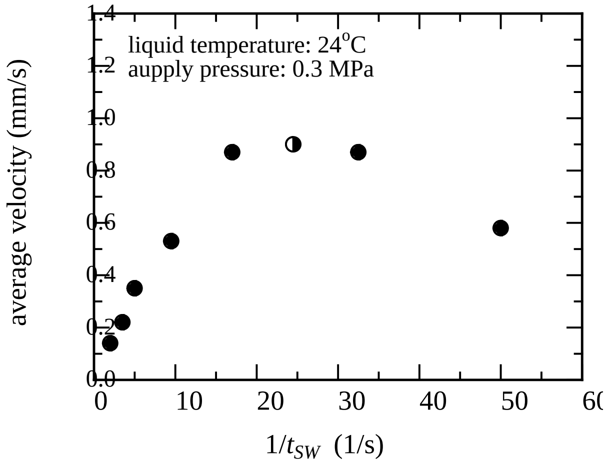


**Fig. 18:** *Characteristics between average velocity and switching time (Kondoh and Yokota, 1997-b)*

Park et al (1999, 2000-a, 2000-b) investigated the behaviour of a 2-port ER valve, which employed a homogeneous ER fluid. Based on the results obtained with this valve, they designed and fabricated a three-port micro ER valve, which had a controllable pressure of 10 kPa and bandwidth of 0.5 Hz with supply pressure of 25 kPa. After that, they built a resonantly driven piezoelectric micro-pump that basically consisted of a bellows as a reciprocating chamber, a piezoelectric actuator for oscillating the bellows and normally closed cantilever type of two check valves, which was driven at resonant frequency (Fig. 19). To obtain further performances by enlarging amplitude of displacement at resonant point, an additional mass was attached to the free end of the piezoelectric actuator. The piezoelectric actuator resonantly excited the bellows of the micro-pump shown in Fig. 19.

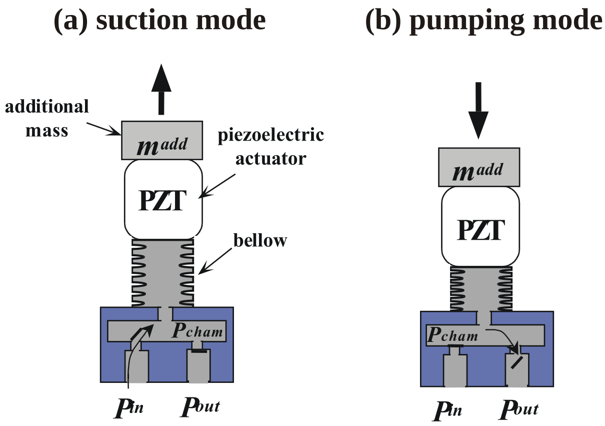


**Fig. 19:** *Configuration and working principle of resonantly-driven piezoelectric micropump (Park, et al 1999)*

The suction and the pumping were performed by momentary differential pressure caused by a periodic volume change in the oscillating chamber. The piezoelectric micro-pump (ϕ 9 × 10 mm) presented a maximum flow rate of 15 mm$^3$/s and maximum pumping pressure of 0.2 MPa (Fig. 20). Then, an open-loop micro position control system was fabricated, as shown in Fig. 21. A displacement amplitude of 23 μm at 2.2 kHz

(1 kV/mm in Fig. 22), and a bandwidth of 0.3 Hz were obtained (Park, et al 2000-b). When the experiments were performed at a lower temperature, a lower performance was observed because the output of the micro-pump decreased due to the higher viscosity (Park, et al 2000-b).

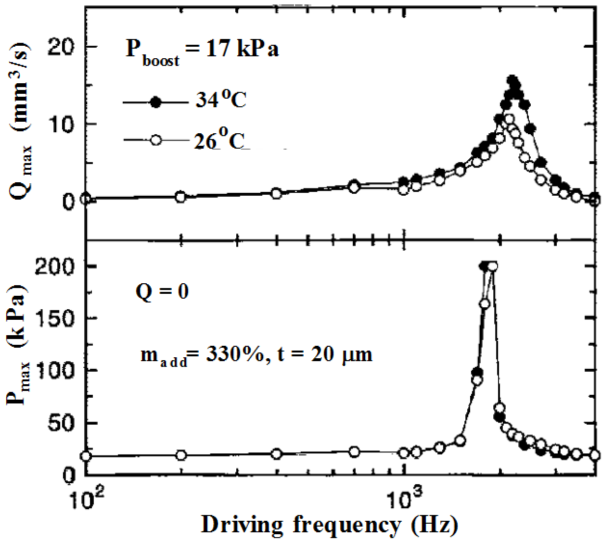


**Fig. 20:** *Frequency characteristics of maximum flow rate and maximum pressure (Park, et al 1999)*

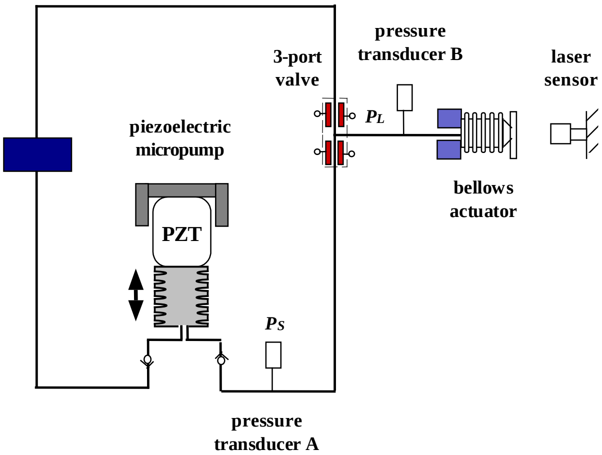


**Fig. 21:** *Schematic of micro hydraulic control system (Park, et al 1999)*

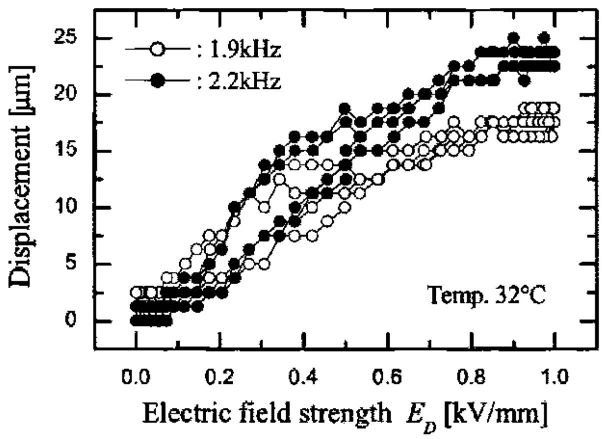


**Fig. 22:** *Static characteristics between electric field strength and bellows-actuator displacement (Park,et al 2000-b)*

In order to obtain a better performance, Park et al (2000-b) proposed a control scheme that changed the phase difference of applied voltages between the upstream and downstream side electrodes of the micro ER valve. The results showed that a phase difference of 240° was effective at low driving frequency and the displacement obtained was 28 μm, which is larger than 23 μm, obtained with 180° (Fig. 23).

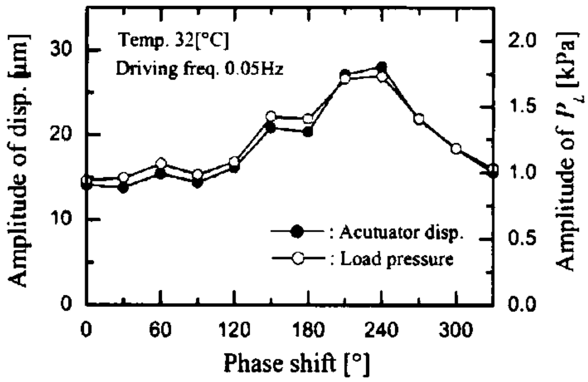


**Fig. 23:** *Experimental results on phase shift (Park, et al 2000-b)*

In recent works, Kondoh and Yokota (1998, 1999-a, 2000-a, 2000-b) manufactured two miniaturized hydraulic actuators with ER fluids and with movable electrodes named METERA (Movable Electrode-Type ER Actuator). The first one was a linear-type (L- METERA), and the second, a rotary-type (R-METERA) – see Fig. 24 and Fig. 25. The design method of the above actuators is presented in the Appendix.

L-METERA mainly consists of two chambers composed of ground fixed electrodes and two movable high voltage electrodes. The ER fluid is supplied to the actuator with a constant pressure and it flows in opposite directions in each channel. When an electric field is applied to the downside electrode, the movable electrodes move to the left direction due to the pressure drop and viscosity caused by the ER effect (Fig. 24-(a)). In the same way, if an electric field is applied to the upside electrode, then the movable electrodes move to the right (Fig. 24-(b)).

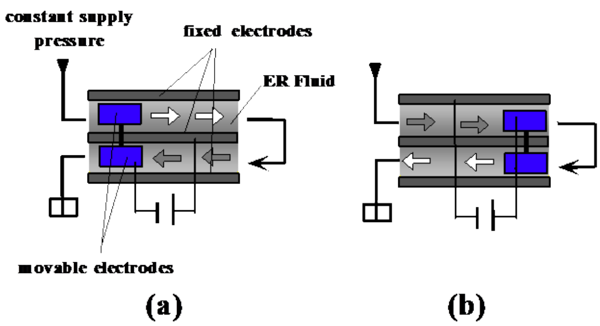

**Fig. 24:** *Principle of L-METERA (Kondoh and Yokota, 1999-a and 2000-a)*

The principle of R-METERA is similar to that of L-METERA. The actuator mainly consists of two pairs of electrodes, which are fixed to the rotor axis (see Fig. 25). The ER fluid flows between each pair of electrodes in opposite rotation. According to the electric field applied to the electrodes the rotor axis rotates either clockwise or counterclockwise.

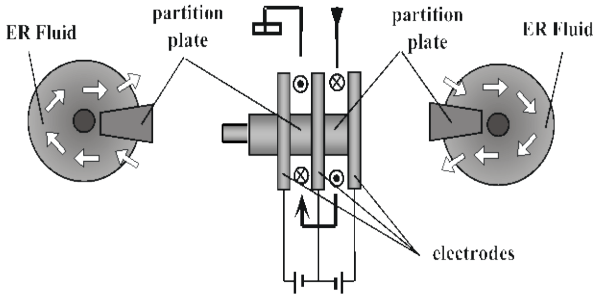


**Fig. 25:** *Principle of R-METERA (Kondoh and Yokota, 1999-a, 1999-b and 2000-a)*

The open loop characteristics of L- METERA and R- METERA were examined by Kondoh and Yokota (1998, 1999-a, 2000-a). For the case of L- METERA, the ER fluid was supplied to the actuator with a constant pressure of 0.14 MPa, and a stroke length of 6.7 mm and a maximum velocity of 2.4 mm/s was obtained. A time lag of 0.4 s was observed due to the magnet coupling and frictions between the casing and Teflon spacers. The output force in static experiments was proportional to the electric field, and the maximum value obtained was 2 N (Fig. 26). For fields lower than 2.7 kV/mm, there was no output force due to friction. In another work, Kondoh and Yokota (2000-b) reported that a stroke length of 125 mm, a maximum velocity of 14 mm/s, and a maximum output force of 12 N were obtained with L-METERA.

For the case of R- METERA, the maximum rotational velocity and the maximum output torque were 7.8 rad/s (75 rpm, which is 16 % of the design value) and 7.8 mN-m (which is 26 % of the design value), respectively (Kondoh and Yokota, 2000-b) – Fig. 27 and Fig. 28. The minimum electric field to make the R- METERA to work was 3 kV/mm (because of friction). This actuator presented inner leakage, causing decrease of output torque. The authors plan future works on its reduction of friction.

The advantage of METERA is that, besides its simple structure, by increasing the area of the electrodes the output force (torque) and the output power of METERA can be easily increased, and controlled independently of the velocity (rotational velocity) – (Kondoh and Yokota, 1999-b). Moreover, due to the viscous drive of METERA, mechanical damages are avoided (Kondoh and Yokota, 2000-b). METERA is suitable to force control actuators and can be applied to deburring machines, clamping devices or force display device and so on.

The characteristics of an ER valve were also studied by Naitoh et al (1995). They placed an ER fluid made of soft particles (polymer core coated by acid titanium) and silicone oil between two parallel electrodes, and visualized and measured the rheological properties of

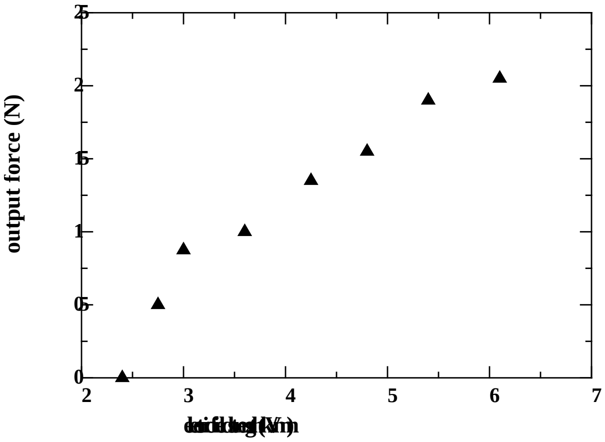


**Fig. 26:** *Static characteristics between electric field strength and outpur force (Kondoh and Yokota, 2000-a)*

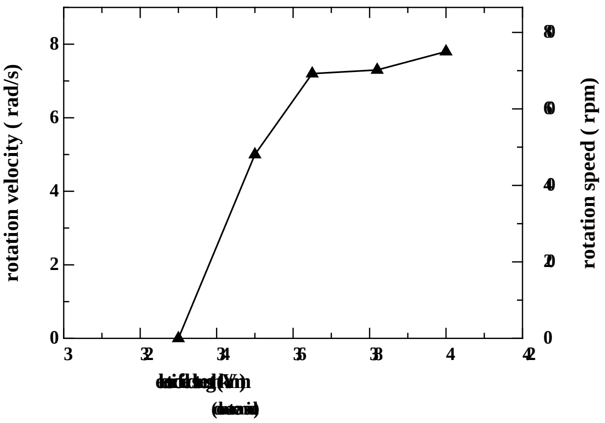


**Fig. 27:** *Static characteristics between rotational velocity and electric field strength (Kondoh and Yokota, 2000-a)*

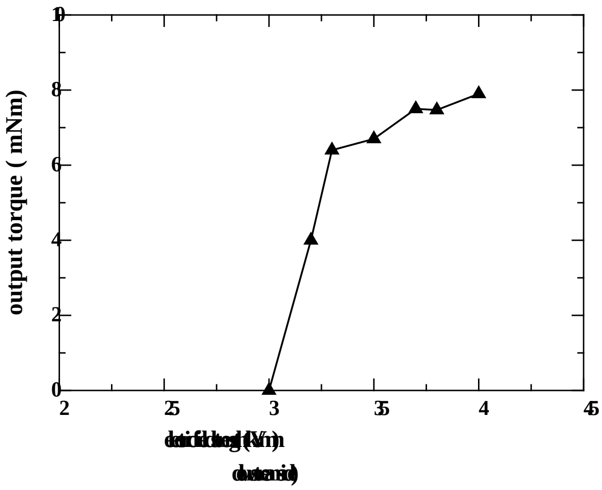


**Fig. 28:** *Static characteristics output torque and electric field strength (Kondoh and Yokota, 2000-a)*

the ER fluid under pressurized flow. They observed that a plug flow was happening in the middle of the channel, and that the pressure drop increased proportionally to the square of the electric field strength up to 2 kV/mm. They also found a large hysteresis around the flow rate of 0 $cm^3/s$.

Researchers from the Inha University, in Korea, have investigated the position control of cylinder systems using ER valves (Choi, et al 1997 and 2000-b). Choi et al (1997) studied the possibility of using ER valves for controllable hydraulic systems. They determined the rheological properties of the ER fluid in a rheometer and, based on the Bingham model, they designed and manufactured a multi-channel plate for the ER valve. The pressure drop of the valve was evaluated as a function of the number of energized electrodes and electric field strength. For 4 kV/mm, the pressure drop increased 25 % when the number of energized electrodes increased from one to three, and 90 % for five energized electrodes (Fig. 29). After that, they formulated an ER valve-cylinder system model and found the governing equations of motion. The position control for the cylinder system was achieved by a neural network control scheme. The results showed that this control system could replace the conventional hydraulic position control system. However, Choi (1998-a) pointed out some issues of the ER valve-cylinder system to employ more realistic system: how to guarantee reliability or durability of the control system against many uncertain parameters such as temperature variation and frictions.

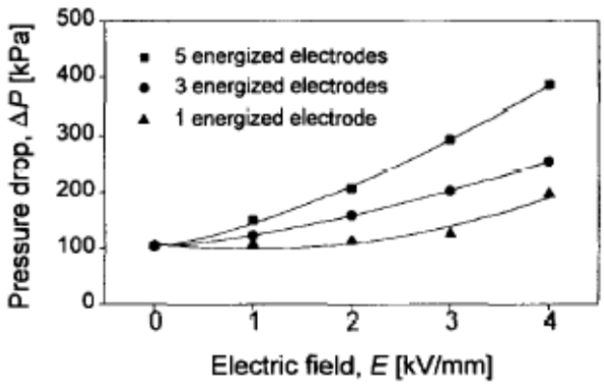


**Fig. 29:** *Field-dependent pressure drop with respect to the number of energized electrodes (Choi, et al 1997)*

Choi et al (2000-b) studied the position control of a cylinder system using ER valves with application to a seaport cargo handling system. They fabricated cylindrical ER valves and evaluated the step responses for pressure drops as a function of the electric field. Then they constructed a bridge circuit and applied it to the position control of the platform of a new type of cargo handling system, which was adaptable to a seaport subjected to time-varying tide. After describing the principle of the cargo handling procedures, the bridge circuit was applied to a laboratory model of cargo handling system. The results showed that the position of the platform was tracked well to the desired motion of the cargo ship. The authors plan to do future works using a large size of cargo handling system activated by ER valve cylinders.

Wolff (1996) constructed a compact ER actuator and studied its dynamical behaviour, which was found to be very good. The actuator moved immediately after switching the field. Moreover, the constant course of velocity when extending showed that the valve was completely closed and that the actuator reached its maximum extending velocity of 0.2 m/s. Due to the hydraulic inductivity of the ER fluid, the static pressure within the piston chamber raised with a sudden braking of the liquid column. This increase in pressure made the piston to accelerate considerably faster and reach a constant extending velocity after approximately 3 ms.

Lee and Liao (2000) studied a different use for ER valves: the control of ink ejection by ER fluids. Although designs using ER fluids as a working median were proposed by Sohn (1996-a, 1996-b), the use of ink with electrorheological properties presented difficulties in practical applications. In order to overcome it, Lee and Liao (2000) proposed a different design of the inkjet printhead device using the ER fluid as a control medium. The dynamic characteristics of the ER fluid valve were determined theoretically using a discretized mechanical model, and then a prototype of the ER valve was fabricated. They studied the effect of the electric field, displacement amplitude and frequency on the system. By increasing field from 0 to 1.25 kV/mm, the pressure ratio of the output chamber decreased from 1 to almost 0.2. The authors observed that the performance ratio was not affected by changes on the frequency in the range of 10 to 70 Hz. However, the controllable range of the performance ratio reduced with the increase of the actuating amplitude.

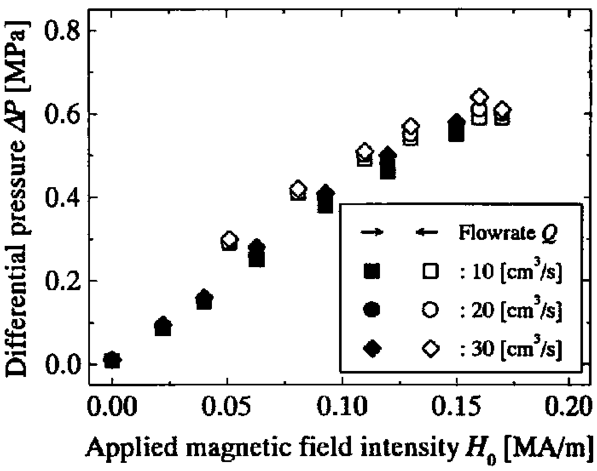


**Fig. 30:** *Measured relation between differential pressure $\Delta P$ and applied magnetic field intensity $H_0$ at 25±1°C (Yokota, et al 1999)*

Nakano et al (1998-c) constructed miniature bellows actuator driven by a pair of PWM controlled ER valves and investigated the control characteristics of the actuator. The PMW ER valve was able to realize the continuous flow rate control in the same manner as an usual valve with moving parts. They concluded that the introduction of overlap duty ratio was very important to smoothly control the actuator without the non-linearity and to improve the control performance.

Not only works on ER fluids are found in control valve applications. Yokota et al (1999) proposed a control valve using MR fluid for fluid control systems. They fabricated a valve with simple structure and measured its static characteristics. From the results they found that the differential pressure $\Delta P$ had little dependence on the flow rate $Q$ because the yield stress of the fluid was much larger than the shear stress caused by the viscosity in the absence of a magnetic field (Fig. 30). The proposed valve showed static characteristics corresponding to a pressure control valve. For $Q$ = 30 $cm^3/s$, $\Delta P$ varied from 0.007 to 0.69 MPa by changing the current from 0 to 0.79 A. They also observed that $\Delta P$ increased linearly (with some hysteresis) with the increase of the applied magnetic field intensity.

### 6.2 Clutches and Brakes

Other types of applications of ER and MR fluids to fluid power, such as clutches and brakes, have also been studied. Both disc and cylindrical clutches have been successfully utilized as the main torque transfer in automotive devices and many researchers have been investigating this subject (Bansbach, 1998; Bullough, et al 1998; Brookfield and Dlodlo 1998; Choi, et al 1998-b, 1999-b and 2000-a; Shimada, et al 1998; Lee, et al 2000).

Shimada et al (1998) proposed a device of rotating regulator with a role of braking device. They conducted experiments using a rotating body immersed in an ER fluid, and measured the static characteristics of the torque and number of revolutions in the device. The shape of the rotating body was of two types: cylindrical disk and conical disk. Depending on the rotating body shape and on the carrier fluid, the braking characteristics were different. For example, in the case of cylindrical disk and silicone oil base, the variation of increment of apparent viscosity was rapid relative to the increase of the electric field strength. However, in the case of conical body and alkylnaphthalen base, the variation was smooth. The authors explained this difference assuming that the increment of apparent viscosity depends on the elasticity of the particles.

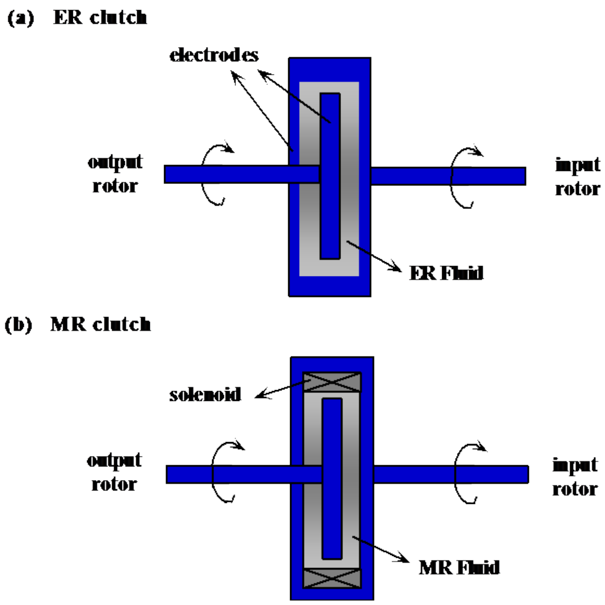


**Fig. 31:** *Geometry of single-disc type ER and MR clutches (Choi, et al 2000-a)*

Choi et al (2000-a) compared the performance characteristics of an ER and a MR clutch, shown in Fig. 31. From their results, they found that the torque of both clutches increased as the field (electric or magnetic) intensity increased, as shown in Fig 32. Moreover, the MR clutch produced much higher controllable torque in the whole range of the angular velocity. For instance, at 5 Hz, the ER clutch produced 0.037 N-m ($E$ = 3 kV/mm) while the MR clutch presented values of 5.13 N-m ($H$ = 240 A/mm). These results suggest that, under the same geometric conditions, a MR clutch is more effective than an ER one, regarding application systems that require high torque range. However, the control response (a PID controller was used) characteristic of the ER clutch was better than that of the MR clutch.

Choi et al (1999-b) studied new actuators represented by bi-directional ER clutch and piezoceramic for active and robust position control of a flexible gantry robot system. First, the dynamic characteristic of the clutch was determined, and after, the governing equations were formulated by treating the inertia of table system and natural frequency of the arm as parameter uncertainties. The results were satisfactory and showed the effectiveness of the system.

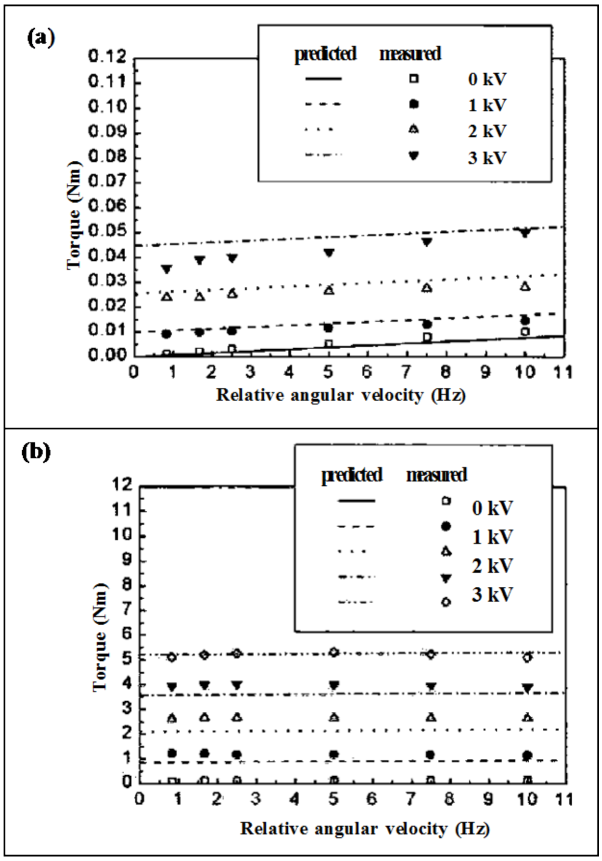


**Fig. 32:** *Field-dependent torque: (a) ER clutch; (b) MR clutch (Choi, et al 2000-a)*

Brookfield and Dlodlo (1996, 1998) developed an ER torque actuator based on a parallel-plate ER clutch driven from a 350 W constant speed motor (see Fig. 33). They applied a closed-loop PID controller for output torque to the ER actuator, and then used the controlled actuator to position a model scale robot arm using a second PID control loop. They obtained a steady state error of less than 0.75 mm with a 2 % settling time of 2.0 s, which is similar to the positioning accuracy of a typical small industrial robot using conventional D.C. servomotor drive. In spite of the dependence of the actuator transfer function on the temperature, they could achieve satisfactory control. After that, they tested the actuator and the arm under a single loop positional control without reference to the actuator torque. A similar steady state error was achieved with a 2 % settling time of 1.4 s. The fast control obtained with an ER actuator was found to make it suitable for positional control of joints on small industrial robots, where rapid and smooth movement is necessary.

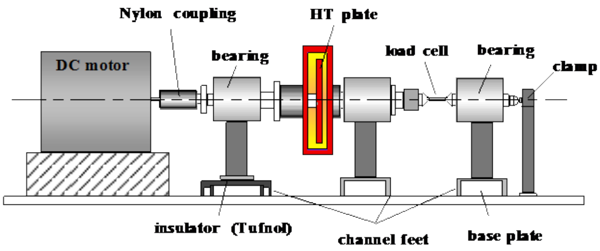


**Fig. 33:** *Basic configuration of an ER actuator used by Brookfield and Dlodlo (1998)*

In a later work, Dlodlo and Brookfield (1999) used three compensator-based controllers in order to control the position of a model scale robot arm attached to the output shaft of an ER actuator. The phase-lead and the phase-lag compensators gave satisfactory responses for the angles of $25^o$, $30^o$, $35^o$ and $40^o$ in terms of stability and steady-state accuracy. Both responses were stable wit h a mean error of $0.5^o$ and $0.7^o$, respectively, after 7 s. However, the lead-lag compensator was found impossible to implement. For small gains the system did not respond, and was unstable for all gains large enough to initiate motion of the arm.

Lee et al (2000) studied two methods to predict the performance of a cylindrical magnetorheological clutch (MRC) and compared the results with experimental data. One of the methods was based on a simplified mathematical model, which considered that the magnetic field distribution within the MR fluid and its viscosity were constant. Assuming that the MR fluid behaves as a Bingham fluid, they found relations for the viscosity and yield stress as a function of the magnetic field strength and used them to estimate the output torque. For the second method, they used softwares to calculate the distribution of the magnetic field (ANSYS) and viscosity (STAR-CD). From the results, they concluded that, for a gap of 1mm, both methods coincided with the experimental data. However, as the gap size increased, the simplified model showed a large discrepancy with the experimental results, while the stabilized response obtained from the CFD (Computational Fluid Dynamics) analysis agreed with the experimental data. As an example, for the case of 8.5 mm of gap, the error of the CFD analysis ($t$ = 1 s) was 5%, while the error of the simplified model was 24 % (Fig. 34). During the transient period (0~0.4 s), both methods showed different results compared to the experimental ones. According to Lee et al (2000), as the shear rate of the fluid changes continuously in the transient period, it is sure that exist different fluid flows other than steady state flow, which is a basic assumption of both numerical simulation. Another factor that, maybe, introduced errors in their simulations is that they used rheological data taken only at one gap size to estimate the viscosity and yield stress as a function of the magnetic field, and then used these data to simulate the performance of the clutch for different gaps. As it is known, some ER and MR fluids can present different rheological properties as a function of gap size, since the chain size will change.

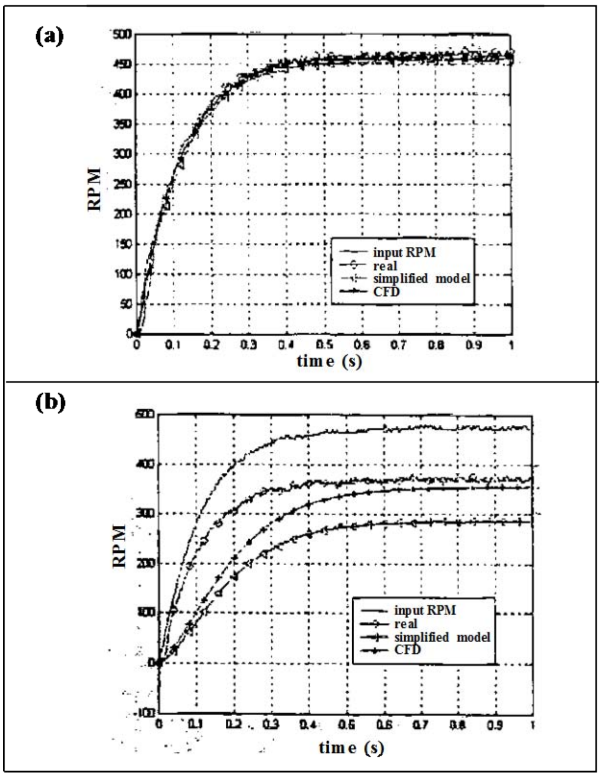


**Fig. 34:** *Comparison of output member velocity (experiments, CFD and simplified model): (a) 48 mm (gap = 1mm); (b) 33 mm (gap = 8.5 mm) – (Lee, et al 2000)*

Furusho and Sakaguchi (1998) developed low inertia ER actuators (torque-controllable ER clutch). These actuators were used in a device that could reproduce the sensation of free movement inside a two-dimensional plane, a sensation in contact with an obstacle such as a wall, a sensation of impact force in ball games and sensations of many kinds of physical systems. The experiments showed that this system could produce a force of more than 25 N in all directions for 3 kV/mm.

Other works have also been done in this field. A method for the position control of a moving table system using ER brake and ER clutch was developed by Choi, et al (1998-b). A favorable position tracking accuracy within ± 5 % with a relatively low cost was achieved. Whittle et a (1998) studied the time dependent solution for flow in a radial ER clutch. Bullough et al (2000) described a method for estimating the running temperature of a demonstrator unsteady motion clutch mechanism, and found that the yield stress for the ER fluid did not influence the level of heat generated. This allows "off-scale" testing and permits the thermal equilibrium calculations to be undertaken without the need to know the relationship between the yield stress and both temperature and shear rate.

### 6.3 Magnetic Fluid Pumps

The development of a magnetic fluid pump, which drives magnetic fluid in a pipe with a traveling magnetic field, has been investigated by Ozaki et al (1998). This kind of a device is advantageous because they don't need any mechanical moving parts or actuators.

When a magnetic field is applied to a MR fluid, the fluid particles get aligned in the direction of the magnetic field. However, when the magnetic field is dropped, the particles loose their magnetization and become randomly orientated because of the thermal agitation. This relaxation process produces a substantial body force in the magnetic fluid with a traveling magnetic field. When a traveling magnetic field is applied, the magnetization of the fluid at the back of the strongest field part is higher than that at the front. The difference of the magnetization of these two sides produces an effective body force in the fluid. As a result, a magnetic field traveling parallel to a pipe axis with appropriate speed makes the fluid to flow in the same direction.

Ozaki et al (1998) have conducted experiments with a water-based magnetic fluid flowing through a concentric pipe. The coils were mounted on the pipe (as shown in Fig. 35), which generated the required travelling magnetic field. A maximum flow rate of 1000 $mm^3$/sec was obtained for magnetic fluid specific weight of around 1.1 (Fig. 36). The pumping pressure lift reached with this experimental setup was about 10 Pa. The authors concluded that, although the performance of the magnetic fluid pump is not the one required by industrial applications, the research carried out in this field will help to design a pump that could be effectively implemented industrially.

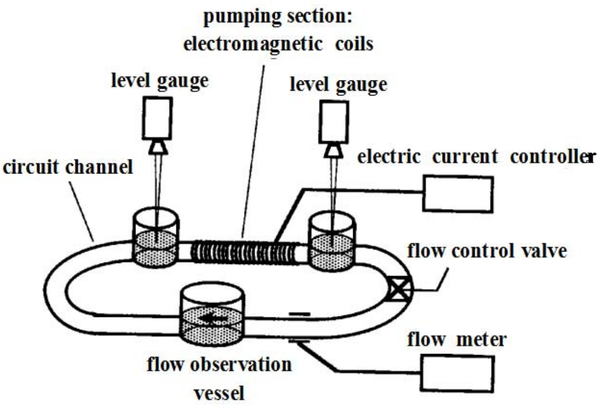


**Fig. 35:** *Schematic layout of the experimental setup of the magnetic pump (Ozaki, et al 1998)*

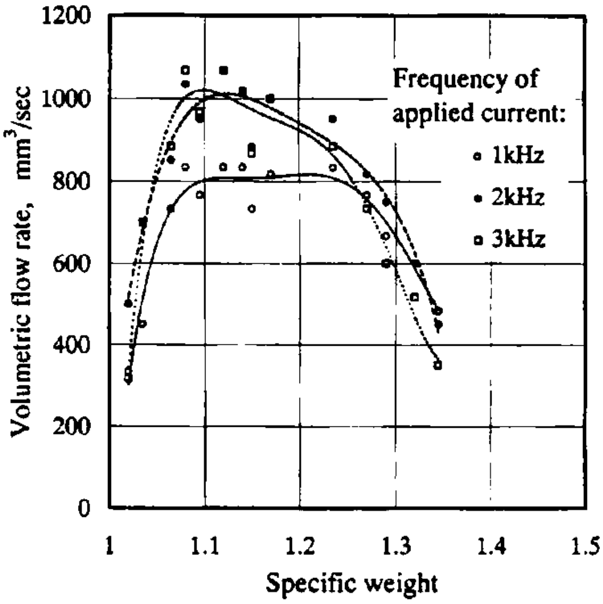


**Fig. 36:** *Volumetric flow rate and specific weight of magnetic fluid (Ozaki, et al 1998)*

## 7 Other Applications of ER and MR Fluids

### 7.1 Damping Systems

A big number of works on damping systems using ER and MR fluids are done. Among the researchers, we can cite: Brooks (1998,), Khusid et al (1998), Furusho and Takesue (1998), Jeon et al (1998), Peel et al (1998), Sproston et al (1998), Tang et al (1998), El Wahed et al (2000), Lee et al (2000), Gordaninejad et al (2000), Lindler and Wereley (2000), and others.

When designing an ER damper, it is necessary to keep in mind that it must be of similar dimensions of existing dampers, develop similar forces at comparable velocities, be readily controllable and take modest amounts of control power at all temperatures. A conventional ER damper operates by altering the properties of the ER fluid as it flows through a simple annular flow path, and the energy is dissipated by viscous loss. The disadvantages of this approach are the large electrode area (which increases power demands), minimum and maximum forces being defined by the viscosity of the fluid itself, and the need to account for the dependence of the fluid properties on the temperature. Since ER fluids are not strong enough when compared to MR fluids, a better solution for using ER fluids in dampers would be to design a damper that employs the best features of a conventional orifice damper and the best features of a conventional ER damper (Brooks, 1998). In Fig. 37 is shown a schematic of this type of damper.

In the absence of an electric field, the ER fluid flows through the central orifice, and $P_1$ is almost equal $P_2$. However, when the field is applied, $P_1 >> P_2$, and the diaphragm deflects closing the central orifice. In this way, the ER fluid flows through the outer orifices. This approach would bring many advantages over the conventional ER damper:

- the ER valve would be significantly smaller (reducing power consumption by at least one order of magnitude),
- existing ER fluids could be used (since they are only required to flex the diaphragm and not to provide the output force),
- a high energy loss independent of temperature would be produced, and
- the operation of the ER damper would be similar to conventional hydraulic dampers.

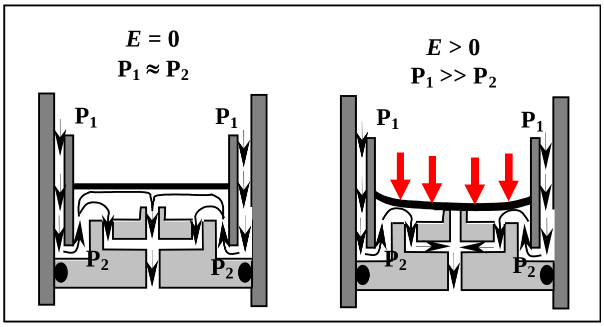


**Fig. 37:** *Schematic of a higher performance ER damper (Brooks, 1998)*

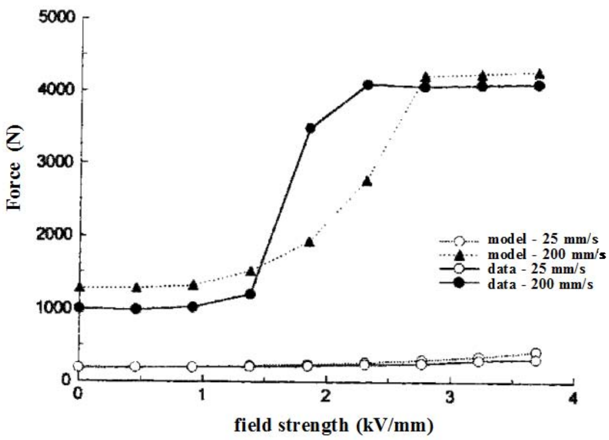


**Fig. 38:** *Force as a function of electric field (minimum and maximum velocities) – (Brooks, 1998)*

Studies have shown that an ER damper designed as shown in Fig. 37 , containing an ER valve of 20 mm of length, width of 28 mm and gap of 0.65 mm, can have a deflection of 1mm in its diaphragm (19 mm of diameter) by the ER pressure loss. This reduces the effective orifice from 2.6 $mm^2$ to 0.9 $mm^2$, causing the force to increase some 3,100 N (Fig. 38). The increase in force due to the ER effect alone is only 139 N, and for this design of damper, the diaphragm acts as an amplifier with a gain of approximately 22 (Brooks, 1998).

Also there has been a great interest in applying the MR technology to automotive application like primary suspension, secondary suspension, engine mounts and so on. Jiang et al (1998) studied the model of a semi-active shock absorber using MR fluids. The semi-active shock absorber is a design between the active and the passive shock absorber, which gives a better performance when compared to the passive shock absorber. The authors chose the quarter-car model to simulate the effect of the semi-active suspension with different control strategies. In order to improve the rider comfort, they used a strategy based on the skyhook model that is a virtual inertial damper. According to this model, damping is required if the velocity of the body of the car is in the same direction as the relative velocity of the suspension system and the body of the car. By measuring the displacements and the relative velocities (obtained by differentiating the displacements), the damping coefficient of the damper was obtained. The control unit of this shock absorber included a microprocessor and a current source. The microprocessor took the data recorded by the displacement sensors, calculated the proper damping coefficient and changed it into the corresponding current value. The fast acting current source changed the current in the coil in terms of milliseconds. Thus this proposed model of a damper for vehicle suspension promises to be an effective control mechanism.

An application of particular interest is that of vibration control in domestic washing machines. Rotational motion of the inner drum or agitator and unbalance of the load gives rise to a disturbing force that excites vibratory motion of the tub, which can become excessive when drum speed is near or at tub resonance. Lord Corporation (Carlson, 2000) fabricated a MR fluid sponge damper that provides a high level of damping of the tub motion at resonance. The dampers are only turned on during the time intervals when the drum passes through resonance. For the case of domestic washing machines, each of both dampers needs to provide 50-150 N of damping force when energized and a residual force smaller than 5 N when turned off. Figure 39 presents a MR fluid sponge damper. According to Carlson, this type of damper does not require any seal or bearings, and only 3 ml of MR fluid are used. The maximum on-state force for this type of damper is about 150 N for 2.0 A. Instead of foam, other suitable absorbent matrix materials can be used: felts, fabrics, metal mesh. The MR fluid used in this device has the consistency of a light grease.

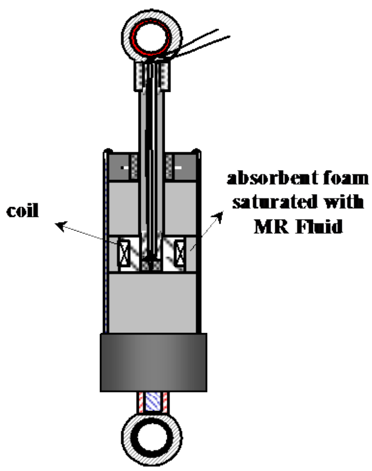


**Fig. 39:** *MR fluid sponge damper (Carlson, 2000)*

Most of the possible applications of MR fluids include dampers whose vibration amplitudes exceed a few millimeters. In order to build a compact damper, the MR fluid valves including coil and magnetic circuit should be integrated into the piston. However, at high piston speeds, the MR fluid is subjected to high shear rates and the time it spends in the magnetic circuit is very small, leading to a decrease in the MR effect. Bölter and Janocha (1998) investigated the behaviour of two MR fluids at high volume flows and short valve lengths. Based on their results, they constructed a MR fluid shock absorber for automobiles and examined the advantages of integrating permanent magnets into the magnetic circuit of shock absorber. The number of ampere-turns of the coil was considerable lowered (34 %) by integrating cylindrical permanent magnets into the magnetic circuit of the shock absorber piston.

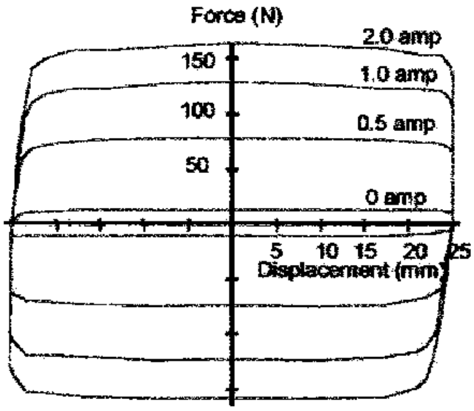


**Fig. 40:** *Force versusdisplacement for a typical MR fluid sponge damper (Carlson, 2000)*

Recent studies have highlighted the advantages of employing squeeze flow mode for ER/MR damping systems (Khusid, 1998). The advantage of this kind of damper when compared to the ones that use flow mode is that the field does not act on a region of flow where the shear rate is high and the contribution of the field-induced stress to the total hydraulic resistance is not relatively low. In addition, most of the shock energy dissipation in flow mode devices occurs inside the ER/MR valve, which means that the heat generated, has to be removed.

## 7.2 Magnetorheological Fluid Based Seals

Nowadays many types and design of mechanical seals and materials have been used. Kordonski et al (1996-b) and Fujita et al (2000) have studied the performance of magnetofluids seal (MFS) based on MR fluids.

The advantages of MFS over other type of seals include:

- superior sealing power (this is specially important for corrosive and toxic fluids)
- low intrinsic friction torque
- almost no wear of the seal and simplicity in restoring serviceability
- ability to operate at high eccentricities and significant runs-out.

Kordonsky and Gorodkin (1996-b) documented that MRF seals offer superior properties when compared to ferrofluid seals. The sealing capacity of MRF seals in the static regime is three times better than that of ferrofluid seals (for $i$ = 2.5 A in Fig. 41), while in dynamic conditions its performance is seven times better when the rotation speed is optimum (Fig. 42). According to the authors, it is quite possible to use MRF seals in commercial applications.

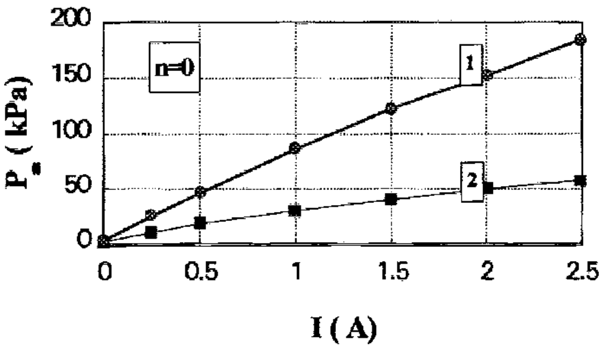


**Fig. 41:** *Static characteristics of the MR fluid (1) and the ferrofluid (2) – (Kordonsky and Gorodkin, 1996-b)*

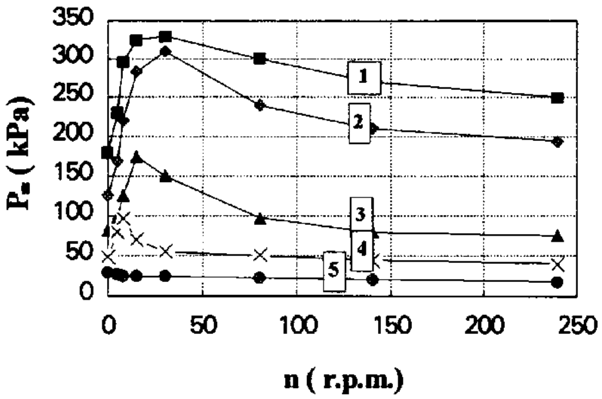


**Fig. 42:** *Effect of the shaft rotation speed on the critical pressure for: MR fluid (1)=2.5A, (2)=1.5A, (3)=1.0A, (4)=0.5A; ferrofluid (5)=1.0A – (Kordonsky and Gorodkin, 1996-b)*

## 7.3 MR and ER Finishing

The abrasiveness of MR (and ER) particles is undesirable in most of the applications, however this property has been exploited in polishing and finishing applications. In order to accelerate removal rates, sometimes non-magnetic abrasive particles are added to the MR fluid (Jacobs, et al 1998). By applying a magnetic field, this abrasive mixture is driven to the interface between the fluid and the component, hence any non-ferrous material may be polished by this technique.

MR fluid finishing (MRF) overcomes some of the disadvantages of the traditional polishing techniques. One distinguishing feature of this technique is that the polishing of the workpiece does not depend on the shape of the polishing pad. Instead, the parameters that control the rate of material removal depend on the properties of the MR fluid used, the strength of the magnetic field applied, and the relative velocity between the workpiece and the MR fluid.

A fundamental advantage of the MR finishing technology from the existing ones is that the polishing tool does not wear, since the recirculated fluid is continuously monitored and maintained. Besides this, polishing debris and heat are continuously removed, and the technique requires no dedicated tooling or special setup. A unique attribute of this process is its determinism that is attained through the use of a well-defined material removal function to eliminate known surface error.

Kordonski and Golini (1998) studied the MR finishing (MRF) process and used a MR fluid composed of micron-sized particles of carbonyl iron in water with a small concentration of stabilizers to prevent sedimentation and to retard oxidation of the iron. In order to augment the material removal rate, nonmagnetic particles of cerium oxide were added to the suspension. In their experiments (Fig. 43), they used the state of the hydrodynamic flow of a magnetorheological polishing fluid throughout a preset converging gap formed by the workpiece surface and a moving rigid wall. An electromagnet, placed below the moving wall, generated a non-uniform magnetic field in the vicinity of the gap. The magnetic field gradient was normal to the wall. The MR polishing fluid was delivered to the wall just above the electromagnet pole pieces. It was pressed by the magnetic field gradient against the wall, acquired the wall velocity, and became a plastic Bingham medium before it entered the gap. Thereafter, a shear flow of plastic MR fluid occurred through the gap, resulting in the development of high stresses in the surface zone and thus, material removal over a portion of the workpiece surface. This area was designated as "polishing spot". The polishing process employed a computer program to determine a schedule for varying the position of the rotating workpiece through the polishing spot. Because of its subaperture nature, this polishing tool may finish complex shapes like aspheres having constantly changing local curvature. For spherical surfaces, for example, the rotating workpiece was swept about a pivot point that was located at its centre of curvature, and varying dwell time at each angular position enabled deterministic material removal from the workpiece surface.

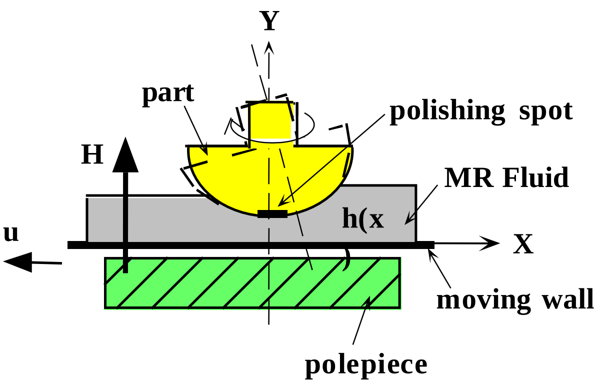


**Fig. 43:** *Scheme of MR finishing (Kordonski and Golini, 1998)*

Due the advantages and simplicity in operation of MR finishing, this process is increasingly being considered for applications.

There are also some researchers investigating on ER finishing. Akagami et al (1998) investigated the polishing of microholes in ceramic discs (used in sensors) using an ER fluid under alternative electric field (Fig. 44). When the frequency of the applied field is high and the relaxation time of the particle is large, the motion of the particles becomes unable to cope with the oscillation of the external field and lead to the formation of clusters and consequently cause an increase in the viscosity. On the other hand, if the frequency of the applied field is low enough the particles are expected to move and respond in a unique way. Utilizing this reciprocate motion, the authors developed a new method of polishing materials. Figure 45 shows a microhole before and after ER polishing.

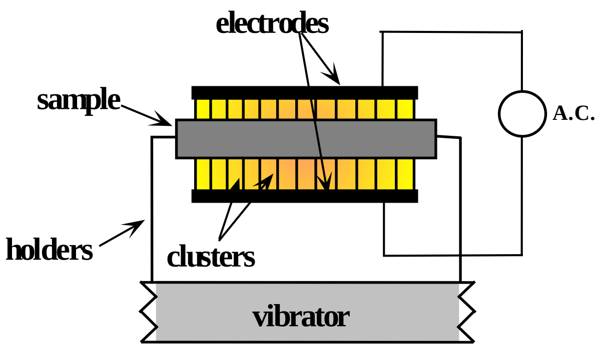


**Fig. 44:** *System proposed for polishing using clusters generated under the application of external electric field, and excited vibrations (Akagami, et al 1998)*

### 7.4 Medical Applications

Research has been done to investigate the use of MR Fluid devices for medical purposes. Although it is in early stages, the idea and the results seem to be promising.

Flores et al (2000) have proposed the use of MR fluids for cancer therapy. As the cancer tissue gets all its nourishment from the blood supplied by the host, if somehow this tissue could be starved for some time by stopping the blood flow to it, the cancer could be destroyed.

It is proposed that, by injecting MR fluid into the blood vessel leading to the cancerous tissue and applying a magnetic field, the MR fluid would form a seal and the blood supply could be clogged locally without affecting other healthy areas. As a result, the supply of blood would stop, and the cancer cells would be destroyed.

There are some advantages in using this proposed idea:

- low cost
- these MR fluids are easily produced

- safety
- this therapy is much simpler than chemotherapy, since the MR fluid only has to be biocompatible and biodegradable, while the chemotherapeutic agent magnetic carriers need to be modified by chemical or biochemical reagents for carrying anticancer drugs.

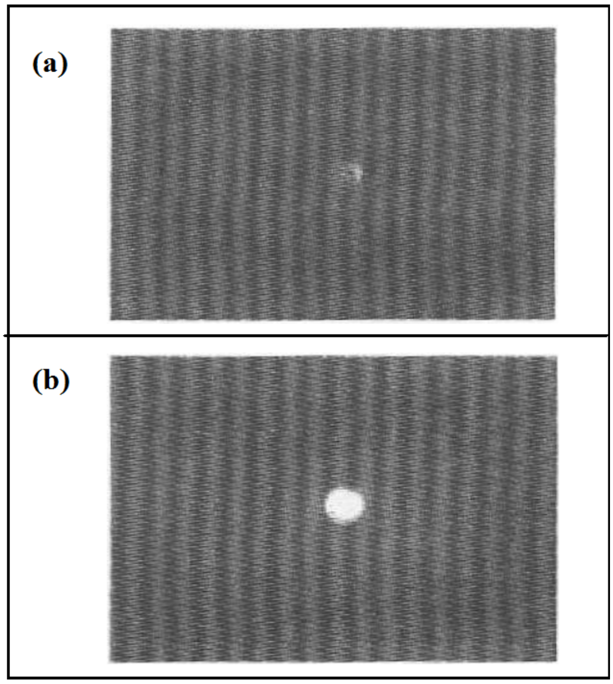


**Fig. 45:** *Microhole (a) before and (b) after ER polishing (Akagami, et al 1998)*

Their studies showed that the strength of the magnetic seal formed is high enough to resist typical capillary blood pressure in the human body, hence this technology can be used for medical applications. This idea is still in its infancy and has to be tested for different fluids and a multiple tubing system (which simulates the human blood circulatory system).

Furusho and Sakaguchi (1998) developed devices using ER actuators that could apply forces to a user. They intend to use the developed force display system to rehabilitation for a virtual therapist. This system is also useful to estimate the control function of muscle for the purpose of rehabilitation. In their work they also present a conceptual sketch of the force display system for virtual surgery.

Zrínyi and Szabó (2000) have proposed a new application for magnetic-gels. The ability of some gels to change shape when subjected to an external magnetic field can be used to create a wide range of motion and to control the shape change and movement similar to that observed in muscles. The authors prepared a material by introducing magnetic particles of colloidal size into chemically cross-linked polyvinyl alcohol hydrogels, and studied the influence of a non-uniform field on it. They observed a significant contraction showing a possibility to use this kind of material to mimic muscular contraction.

## 8 Conclusions

Over the past few years, more and more attention has been paid to the use of magnetorheological (MR) and electrorheological (ER) fluids in commercial applications. The usefulness of these fluids is recognized in various industries, and some applications already began to appear on the market. The mechanisms of magnetorheology and electrorheology need to be better understood. Practical issues such as stability of the fluids against sedimentation and centrifugation, weight of the coils and heating are challenges still to be overcome. The development of new devices and applications motivate the fluid power community to continue their investigations in this field.

## Nomenclature

| | | |
|---|---|---|
| $A$ | sectional area of chamber | [m$^2$] |
| $B$ | flux density | [Tesla] |
| $F$ | force | [N] |
| $F_{\max}$ | maximum output force | [N] |
| $G$ | complex modulus | [Pa] |
| $G'$ | storage modulus | [Pa] |
| $G''$ | loss modulus | [Pa] |
| $H$ | gap size (L-METERA) | [m] |
| $h$ | gap size (R-METERA) | [m] |
| $J_{\max}$ | maximum output power | [W] |
| $J_{\mathrm{s}}$ | saturation magnetization | [Tesla] |
| $L$ | length of the channel (L-METERA) | [m] |
| $l$ | length of the channel (R-METERA) | [m] |
| $P_{\mathrm{ERV}}$ | differential pressure | [Pa] |
| $P_{\mathrm{s}}$ | pressure supplied to actuator | [Pa] |
| $r$ | radius of electrode (R-METERA) | [m] |
| $T_{\max}$ | maximum torque (R-METERA) | [N·m] |
| $t_{\mathrm{SW}}$ | switching time | [s] |
| $V_{\max}$ | maximum velocity (L-METERA) | [m/s] |
| $W$ | width of the channel (L-METERA) | [m] |
| $w$ | width of the channel (R-METERA) | [m] |
| $\delta$ | loss angle | [Pa] |
| $\Phi$ | particle volume fraction | [-] |
| $\gamma$ | strain | [-] |
| $\dot{\gamma}$ | shear rate | [s$^{-1}$] |
| $\eta$ | viscosity | [Pa·s] |
| $\mu$ | viscosity in absence of field | [Pa·s] |
| $\tau$ | shear stress | [Pa] |
| $\tau_y$ | yield stress | [Pa] |
| $\tau_{\psi,\max}$ | maximum yield stress | [Pa] |
| $\omega_{\max}$ | maximum angular velocity (R-METERA) | [rad/s] |

## Appendix - Design Methodology for an ER Actuator (Kondoh and Yokota, 1997-b and 1998)

When an ER fluid flows through a rectangular channel firmed by electrodes, its characteristics between the differential pressure $P_{\mathrm{ERV}}$ and the flow rate $Q_{\mathrm{ERV}}$ can be expressed by:

$$P_{\mathrm{ERV}} = \frac{2L}{H}\tau_{\mathrm{y}}(E) + \frac{12\mu L}{W H^3} Q_{\mathrm{ERV}} \quad \text{(A-1)}$$

where $L$ and $W$ are the length and width of the channel, $H$ is the gap size, $\tau_{\mathrm{y}}(E)$ is the yield stress depending on the electric field $E$ and $\mu$ is the viscosity of the ER fluid in absence of field (Kondoh and Yokota, 1997-b and 1998). Equation (A-1) is employed as a fundamental equation in designing ER valves.

The performance indices (the dynamic range in load pressure with the control of port blocked and maximum load flow rate), which can be obtained by using equation (A-1), are important parameters when designing ER valves, and are calculated as:

$$\left(P_{\mathrm{L,max}} - P_{\mathrm{L,min}}\right) = \frac{2L}{H}\tau_{\mathrm{y,max}} \quad \text{(A-2)}$$

$$Q_{\mathrm{L,max}} = \left(P_{\mathrm{s}} - \frac{2L}{H}\tau_{\mathrm{y,max}}\right)\frac{W H^3}{12\mu L} \quad \text{(A-3)}$$

where $P_s$ is the supply pressure. The relantionship between load pressure and electric field strength with control port blocked are obtained as follows by using equation (A-1)

$$P_{\mathrm{L}} = \frac{2L}{H}\tau_{\mathrm{y}}(E) + \frac{1}{2}\left(P_{\mathrm{s}} - \frac{2L}{H}\tau_{\mathrm{y,max}}\right) \quad \text{(A-4)}$$

Once the parameters of the valve are defined (($P_{\mathrm{L,max}}$ - $P_{\mathrm{L,min}}$) and $Q_{\mathrm{L,min}}$), and having $P_{\mathrm{s}}$, $\tau_{\mathrm{y,max}}$ and $\mu$ , the dimensions of the channel can be obtained by equations (A-2) and (A-3).

The characteristics of the actuator depend on dimensions of the rectangular channel formed from the electrodes and the sectional area of the chamber. When an ER fluid flows through a rectangular channel, its characteristics between the differential pressure $P_{\mathrm{ERV}}$ and the flow rate $Q_{\mathrm{ERV}}$ can be expressed by equation (A-1). The maximum output force ($F_{\max}$) and the maximum output power ($J_{\max}$) are design parameters of the ER actuator. If the area of the rectangular channels composed of electrodes is much smaller than that of the chambers (which the slide electrodes are inserted into), and both chambers and electrodes have the same dimensions ($W$, $L$, $H$ and $A$), then the design parameters of a L-METERA can be obtained by using equation (A-1):

$$F_{\max} = \frac{2L}{H} A\, \tau_{\mathrm{y,max}} \quad \text{(A-5)}$$

$$J_{\max} = F_{\max} V_{\max} = \frac{W H^2}{2\mu}\left(P_{\mathrm{s}} - \frac{2L}{H}\tau_{\mathrm{y,max}}\right)\tau_{\mathrm{y,max}} \quad \text{(A-6)}$$

where $A$ is the sectional area of the chamber, $V_{max}$ is the maximum velocity of the linear-type actuator, $P_s$ is the pressure supplied to the actuator. In order to have an actuator that gives $F_{max}$ = 6 N and $J_{max}$ = 0.3 W, Kondoh and Yokota (1998) found that the dimensions of the channels and the chamber should be ($P_s$ = 0.14 MPa, $\tau_{y,max}$ = 1.4 kPa, $\mu$ = 65 mPa·s): $L$ = 20 mm, $W$ = 26 mm, $H$ = 0.5 mm, $A$ = 52 mm$^2$.

For designing the R-METERA, the maximum output torque $T_{max}$ and the maximum output power $J_{max}$ are obtained by using equation (A-1) and are shown below:

$$T_{\max} = 2\,l\,w\,r\,\tau_{y,\max} \quad \text{(A-7)}$$

$$J_{\max} = T_{\max}\,\omega_{\max} = \frac{w h^2}{2\mu}\left(P_s - \frac{2l}{h}\tau_{y,\max}\right)\tau_{y,\max} \quad \text{(A-8)}$$

For $T_{max}$ = 0.03 Nm and $J_{max}$ = 1.5 W, W, Kondoh and Yokota (1999-b) found that the dimensions of the channels and the chamber should be ($P_s$ = 0.2 MPa, $\tau_{y,max}$ = 1.1 kPa, $\mu$ = 0.2 Pa·s): $r$ = 15 mm, $w$ = 14 mm, $h$ = 1.5 mm.

## References


**Akagami, Y., Nisimura, S., Ogasawara, Y., Fujita, T., Jeyadevan, B., Nuri, K.** and **Itoh, K.** 1998. Polishing of Microholes using ER Fluid under Alternative Electric Field. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 803-808.

**Akagami Y., Asari, K., Jeyadevan, B., Fujita, T.** and **Umehara, N.** 2000. ER Fluid Finishing Using Rotating Electrode. *7th Int. Conference on electrorheological (ER) Fluids and Magneto-Rheological (MR) Suspensions*, pp. 833-838.

**Asako, Y. Ono, S., Aizawa, R.** and **Kawakami, T.** 1995. Properties of electrorheological Fluids Containing Numerously Sulfonated Polymers Particles. *Progress in Electrorheology - Science and Technology of Electrorheological Fluids*, eds. K. O. Havelka and F. E. Filisko, Plenum Press, pp. 147-156.

**Bansbach, E. A.** 1998. Torque Transfer Apparatus Using Magnetorheological Fluids. *US-Patent 5,779,013*.

**Block, H. and Rattray, P.** 1995. Recent Developments in ER Fluids. *Progress in Electrorheology - Science and Technology of Electrorheological Materials*, eds. K. O. Havelka and F. E. Filisko, Plenum Press, pp. 19-42.

**Bolter, R.** and **Janocha, H.** 1998. Demands on MR Fluid Energy Transducers in Shock Absorbers. Actuator 98, *6th Int. Conf. on New Actuators*, pp. 426-429.

**Brookfield, D. J.** and **Dlodlo, Z. B.** 1996. Transfer Function of and Electro-Rheological Actuator. *5th Int. Conference on Electro-Rheological Fluids, Magneto-Rheological Suspensions and Associated Technology*, pp. 300-317.

**Brookfield, D. J.** and **Dlodlo, Z. B.** 1998. Robot Torque and Position Control Using an Electrorheological Actuator. *Proc. Instn. Mech. Engrs.*, V. 212, Part I, pp. 229-238.

**Brooks, D. A.** 1998. High Performance Electro-Rheological Dampers. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 689-696.

**Bullough, W. A., Johnson, A. R., Tozer, R.** and **Makin, J.** 1998. Methodology, Performance and Problems in ER Clutch Based Positioning Mcechanisms. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 623-630.

**Bullough, A. W., Makin, J., Johnson, A. R.** and **Tozer, R.** 2000. Interactive Dynamic, Thermodynamic and Electrical Studies on an Electronically Adjustable ER Linear Reversing. *7th Int. Conference on electrorheological (ER) Fluids and Magneto-Rheological (MR) Suspensions*, pp.274-285.

**Carlson J. D., Catanzarite, D. M.** and **St. Clair, K. A.** 1996. Commercial Magnetorheological Fluid Devices. *5th Int. Conference on Electro-Rheological Fluids, Magneto-Rheological Suspensions and Associated Technology*, pp. 20-28.

**Carlson, J. D.** and **Jolly, M. R.** 2000. MR Fluid Foam and Elastomer Devices. *Mechatronics*, 10, pp. 555-569.

**Carlson, J. D.** 2000. Low-Cost MR Fluid Sponge Devices. 7th Int. Conference on Electrorheological (ER) Fluids and Magneto-Rheological (MR) Suspensions, pp. 633-640.

**Choi, S. B., Cheong, C. C., Jung, J. M.** and **Choi, Y. T.** 1997. Position Control of an ER Valve-Cylinder System via Neural Network Controller. *Mechatronics*, V.7, No.1, pp. 37-52.

**Choi, S.B.** 1998-a. Control Characteristics of ER Devices. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 764-771.

**Choi, S. B., Kim, S. L., Lee, H. G.** and **Nam, M. H.** 1998-b. Position Control of a Moving Table Using ER Clutch and ER Brake. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 661-669.

**Choi, S. B., Han, S. S., Kim, H. K.** and **Cheong, C. C.** 1999. $H_\infty$ Control of a Flexible Gantry Robot Arm Using Smart Actuators. *Mechatronics*, V.9, pp. 271-286.

**Choi, S. B., Hong, S. R., Park, W. W., Cheong, C. C.** and **Park y. K.** 2000-a. Comparison of Field-Controlled Characteristics Between ER and MR Clutches. *7th Int. Conf. on ER Fluids and MR Sus-*

*pensions*, pp. 603-610.

**Choi, S. B., Sung, K. G., Chung, D. D.** and **Kim, H. S.** 2000-b. Active Control of ER Valves With Application to Seaport Cargo Handling System. *7th Int. Conference on electrorheological (ER) Fluids and Magneto-Rheological (MR) Suspensions*, pp. 767-774.

**Dlodlo, Z. B.** and **Brookfield, D. J.** 1999. Compensator-based Position Control of an Electrorheological Actuator. *Mechatronics*, 9, pp. 895-917.

**Dyke, S. J., Spencer, B. F., Sain, M. K.** and **Carlson, J. D.** 1996. Modeling and Control of Magnetorheological Dampers for Seismic Response Reduction. *Smart Materials and Structures*, Vol.5, pp. 565-575.

**El Wahed, A., Sproston, J. L.** and **Schleyer, G. K.** 2000. Comparison Between Electrorheological and Magnetorheological Fluids Subjected to Impulsive Loads. *7th Int. Conference on electrorheological (ER) Fluids and Magneto-Rheological (MR) Suspensions*, pp. 401-410.

**Fees, G.** 2001. Study of the Static and Dynamic Properties of a Highly Dynamic ER Servo Drive. *Ölhydraulik und Pneumatik*, Vol. 45, Nr. 1.

**Felt, D. W., Hagenbuchle, M., Liu, J.** and **Richard, J.** 1996. Rheology of a Magnetorheological Fluid. *Journal of Intelligent Material Systems and Structures*, Vol. 7, pp. 589-593.

**Filisko, F. E.** 1995. Overview of ER Technology. *Progress in Electrorheology - Science and Technology of Electrorheological Materials*, eds. K. O. Havelka and F. E. Filisko, Plenum Press, pp. 3-18.

**Filisko, F. E., Henley, S.** and **Quist, G.** 1998. Recent Developments in the Properties and Composition of ER Fluids.*4th International Conference on Intelligent Materials*, pp. 114-117.

**Filisko, F. E.** and **Henley, S.** 2000. Parameters Affecting Lamellar Formations in ER Fluids: An Alternative Model for ER Activity. *7th Int. Conference on Electrorheological (ER) Fluids and Magneto-Rheological (MR) Suspensions*, pp. 145-153.

**Flores, G. A., Sheng, R.** and **Liu, J.** 2000. Medical Application of Magnetorheological Fluids - A Possible New Cancer Therapy. *7th Int. Conference on Electrorheological (ER) Fluids and Magneto-Rheological (MR) Suspensions*, pp. 716-723.

**Fujita, T., Jeyadevan, B., Kuzuno, E., Nakagawa, N.** and **Hioki, S.** 1998. Formation of Clusters and Their Effect on the viscosity of Magnetic and electrorheological Fluids. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 578-585.

**Fujita, T., Yoshimura, K., Seki, Y., Dodbiba, G., Miyazaki, T** and **Numakura, S.** 2000. Characterization of Magnetorheological Suspensions for Seal.

*7th Int. Conference on Electrorheological (ER) Fluids and Magneto-Rheological (MR) Suspensions*, pp. 709-715.

**Furusho, J., Takesue, N., Zhang, G.** and **Sakaguchi, M.** 1998. Motion Control of Robot Arms with Variable Damper Using Liquid Crystalline Polymers. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 713-720.

**Furusho, J.** and **Sakaguchi, M.,** 1998. New Actuators Using ER Fluid and Their Applications to Force Display Devices in Virtual Reality and Medical Treatments. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 755- 763.

**Gandhi, M. V.** and **Thompson, B. S.,** 1992. *Smart Materials and Structures*. Chapman & Hall, pp. 137-174.

**Ginder, J. M.** 1996. Rheology Controlled by Magnetic Fields. *Encyclopedia of Applied Physics*, Vol. 16, pp. 487-503.

**Ginder, J. M., Nichols, M. E., Elie, L. D.** and **Tardiff, J. L.** 1999. Magnetorheological Elastomers: Properties and Applications. *Smart Structures and Materials 1999: Smart Technologies, Proceedings of SPIE*, Vol. 3675, pp. 131-138.

**Ginder, J. M., Nichols, M. E., Elie, L. D.** and **Clark, S. M.** 2000. Controllable-Stiffness Components Based on Magnetorheological Elastomers. *Smart Structures and Materials 2000: Smart Structures and Integrated Systems, Proceedings of SPIE*, Vol. 3985, pp. 418-425.

**Gordaninejad, F.** and **Breese, D. G.** 2000. Heating of Magnetorheological Fluid Dampers: An Experimental Study. *7th Int. Conference on Electrorheological (ER) Fluids and Magneto-Rheological (MR) Suspensions*, pp. 629-638.

**Havelka, K. O'L.** 1995. Novel Materials for Electrorheological Fluids. *Progress in Electrorheology - Science and Technology of Electrorheological Materials*, eds. K. O. Havelka and F. E. Filisko, Plenum Press, pp. 43-54.

**Henley, S.** and **Filisko, F. E.** 1999. Flow Profiles of electrorheological Suspensions: An alternative Model for ER Activity. *Journal of Rheology*, **43**(5), pp. 1323-1336.

**Inoue, A., Ide, Y., Maniwa, S., Yamada, H.** and **Oda, H.** 1998. Properties of ER Fluids Comprised of Liquid Crystalline Polymers. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp.384-392.

**Ishino, Y., Maruyama, T., Ohsaki, T., Endo, S., Saito, T.,** and **Goshima, N.** 1995. Anhydrous Electrorheological Fluid Using Carbonaceous Particle as Dispersed Phase. *Progress in Electrorheology - Science and Technology of Electrorheological Fluids*, eds. K. O. Havelka and F. E. Filisko, Plenum Press, pp. 137-146.

**Jacobs, S. D., Kordonski, W. I.** and **Pollicove, H. M.** 1998. Precision Control of Aqueous Magnetorheological Fluids for Finishing Optics. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 861-869.

**Jeon, Y. S., Choi, Y. T.** and **Cheong, C. C.** 1998. Feedback Control for Vibration Attenuation in an ER Engine Mount. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 721-729.

**Jiang, F. Q., Wang, Z. W., Wu, J. Y.** and **Jhou, L. W.** 1998. Magnetorehological Materials and Their Applications in Shock Absorbers. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 494-501.

**Jolly, M. R., Carlson, J. D.** and **Munoz, B. C.** 1996. A Model of the Behaviour of Magnetorheological Materials. *Smart Materials and Structures*, Vol.5, pp. 607-614.

**Jolly, M. R., Bender, J. W.** and **Carlson, J. D.** 1998. Properties and Applications of Comemrcial Magnetorheological Fluids. *SPIE 5th Annual Int. Symposium on Smart Structures and Materials*, San Diego, CA, 15 March.

**Jolly, M. R.** and **Nakano, M.** 1998. Properties and Applications of Comemrcial Controllable Fluids. *6th International Conference on New Actuators*, pp. 411-416.

**Kimura, H., Aikawa, K., Masubuchi, Y., Takimoto, J. I.** and **Koyama, K.** 1998. Electrically Induced Phase Inversion in Polyurethane/Dimethylsiloxane Blend. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 429-435.

**Kito, H., Tajiri, K., Orihara, H., Ishibashi, Y., Doi, M.** and **Inoue, A.** 1998. A Novel Mechanism of Electrorheological Effect in Polymer Blends. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 401-407.

**Kohl, M., Dürr, S., Just, E.** and **Pirck, D.** 1998. Development of Electrorheological Microactuators. *6th International Conference on New Actuators*, pp. 430-433.

**Kohl, M.** 2000. Fluidic Actuation by Electrorheological Microdevices. *Mechatronics*, V.10, pp. 583-594.

**Kondoh, Y., Yokota, S., Yoshida, K.** and **Edamura, K.** 1995. A Fluid Control Valve Making Use of Electro-Rheological Fluid. *The 4th Scandinavian International Conference on Fluid Power*, pp. 830-841.

**Kondoh, Y., Yokota, S.** and **Yoshida, K.** 1996. A Mini Valve in Application of Electro-Rheological Fluids, *Proc. of IFAC, 13th Triennial World Congress*, San Francisco, Vol. A, pp. 493-498.

**Kondoh, Y.** and **Yokota, S.** 1997-a. Micro Control Valves by Making Use of Electro-Rheological Fluids, (Control of One-Link Manipulator with the Micro ER Valve), *Proceedings of ASME+IMECE, FPST-Vol4/DSC-Vol.63, Fluid Power Systems and Technology: Collected Papers ASME 1997*, Dallas, pp. 55-60.

**Kondoh, Y.** and **Yokota, S.** 1997-b. Micro In-Pipe Mobile Machines by Making Use of an Electro-Rheological Fluid. *Proc. of IROS'97*, Grenoble, pp. 1672-1677.

**Kondoh, Y.** and **Yokota, S.** 1997-c. A Control Valve by Making Use of an Electro-Rheological Fluid (Design and Fabrication of a Micro Control Valve). *Proc. of 2nd Asian Control Conference*, Seoul, vol. III, pp. 307-310.

**Kondoh, Y., Yokota, S.** and **Yoshida, K.** 1997. A Control Valve by Making Use of an Electro-Rheological Fluid (Fundamental Characteristics and Application to a Pressure Control Valve), *Proc. of the 4th International Conference on Fluid Power Transmission and Control ('97 ICFP)*, Hangzhou, pp. 71-76.

**Kondoh, Y.** and **Yokota, S.** 1998. Actuators Making Use of electro-Rheological Fluids (A Small-Sized Linear ER Actuator). *Proc. of 3rd Int. Conference on Advanced Mechatronics, JSME*, October, Okayama, Japan, pp. 639-643.

**Kondoh, Y.** and **Yokota, S.** 1999-a. Movable Electrode-type ER Actuator (Proposal of Linear-type and Rotary-type METERA). *Proc. of IROS'99*, Kyongjyu, pp. 1757-1761.

**Kondoh, Y.** and **Yokota, S.** 1999-b. Actuators Making Use of Electro-Rheological Fluids: Movable Electrode Type ER Actuators. *J. Intelligent Material Systems and Structures*, V.10, pp. 718-722.

**Kondoh, Y.** and **Yokota, S.** 2000-a. Actuators Making Use of Electro-Rheological Fluids (Proposition of Movable Electrode Type ER Actuators). *7th Int. Conference on Electrorheological (ER) Fluids and Magneto-Rheological (MR) Suspensions*, pp. 735-742.

**Kondoh, Y.** and **Yokota, S.** 2000-b. Applications of ER Fluids to Fluid Power Systems (Proposition of Micro ER Valves and Novel Hydraulic Actuators: METERA), *Actuator 2000, Proc. of 7th International Conference on New Actuators*, Bremen, pp. 131-134.

**Kordonski, W.I.** and **Jacobs, S. D.** 1996-a. Magnetorheological Finishing. 5th Int. Conference on Electro-Rheological Fluids, Magneto-Rheological Suspensions and Associated Technology, pp. 1-12.

**Kordonski, W. I.** and **Gorodkin, S. R.** 1996-b. Magnetorheological Fluid-Based Seal. 5th Int. Conference on Electro-Rheological Fluids, Magneto-Rheological Suspensions and Associated Technology, pp.704-709.

**Kordonski, W.** and **Golini, D.** 1998. Progress Update in Magnetorheological Finishing. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 837-843.

**Kordonski, W.** and **Golini, D.** 2000. Fundamentals of Magnetorheological Fluid Utilization in High Precision Finishing. *7th Int. Conf. on Electrorheological Fluids and Magnetorheological Suspensions*, pp. 682-692.

**Kormann, Cl., Laun, H. M.** and **Richter, H. J.** 1996. MR Fluids with Nano-Sized Magnetic Particles. *5th Int. Conference on Electro-Rheological Fluids, Magneto-Rheological Suspensions and Associated Technology*, pp. 362-367.

**Khusid, B., Acrivos, A., Khodorkovsky, Y.** and **Beltran, M.** 1998. Electrorheological Squeeze-Flow Shock Absorber. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 705-712.

**Lee, U., Kim, D., Hur, N.** and **Jeon, D.** 2000. Design Analysis and Experimental Evaluation of an MR Fluid Clutch. *7th Int. Conference on Electrorheological (ER) Fluids and Magneto-Rheological (MR) Suspensions*, pp. 674-681.

**Lee, C. Y.** and **Liao, W. C.** 2000. Characteristics of an Electro-Rheological Fluid Valve used in an Inkjet Printhead. *Smart Materials Structures*, V.9, pp. 839-847.

**Lee, D. Y.** and **Wereley, N. M.** 2000. Quasi-Steady Herschel-Bulkley Analysis of Electro- and Magneto-Rheological Flow Mode Dampers. *7th Int. Conference on Electro-Rheological Fluids, Magneto-Rheological Suspensions*, pp. 579-586.

**Lindler, J. E.** and **Wereley, N. M.** Double Adjustable Shock Absorbers Using Electrorheological Fluid. *7th Int. Conference on Electrorheological (ER) Fluids and Magneto-Rheological (MR) Suspensions*, pp. 783-790.

**Naitoh, T., Nakada, T.** and **Edamura, K.** 1995. Study on Flow Characteristics of ER Fluid Between Two Parallel Electrodes. *The 4th Scandinavian International Conference on Fluid Power*, pp. 825-829.

**Nakano, M., Ito, K., Konno, M.** and **Aizawa, R.** 1998-a. Dynamic Viscoelasticity in Oscillatory Slit Flow of an ER Suspension Containing Sulfonated Polymer Particles, *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 232-239.

**Nakano, M.**, **Yamamoto, H.** and **Jolly, M.** 1998-b. Dynamic Viscoelasticity of a Magnetorheological Fluid in Oscillatory Slit Flow, *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 551-559.

**Nakano, M., Minagawa, S.** and **Hagino, K.** 1998-c. PWM Flow Rate Control of ER Valve and Its Application to ER Actuator Control. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 772-779.

**Narumi, T., Hayashibe, T., Hasegawa, T.** and **Asako, Y.** 2000. Converging and Diverging Flow of Electrorheological Fluid in Minute Channels. *7th Int. Conference on Electro-Rheological Fluids, Magneto-Rheological Suspensions*, pp. 180-187.

**Orihara, H., Doi, M.** and **Ishibashi, Y.** 1998. Two Types of Electrorheological Effect in Polymer Blends. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 367-373.

**Ozaki, K., Korenaga, A.** and **Ichiki, M.** 1998. Pumping Characteristics of Magnetic Fluid Pump. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 879-886.

**Park, J. H., Yoshida, K.** and **Yokota, S.** 1999. Micro Fluid Control System Using Homogeneous ER Fluids. *Proceedings of IROS'99*, Kyongjyu, pp. 1063-1068.

**Park, J. H., Yoshida, K.** and **Yokota, S.** 2000-a. Micro ER Valve Using Homogeneous ER Fluids and Its Application to Micro Fluid Control System, *Proc. of IECON-2000*, Nagoya, October, pp. 1809-1814.

**Park, J. H., Yoshida, K.** and **Yokota, S.** 2000-b. Micro Fluid Control System for Micromachines. *Proceedings of FLUCOME 2000*, Canada, August (printed in CD).

**Peel, D. J., Bullough, W. A.** and **Stanway, R.** 1998. ER/MR Long Stroke Damper: Performance Testing, Modeling and Control Strategy Simulation. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 744-751.

**Phulé. P. P.** 1998. Synthesis of Novel Magnetorheological Fluids. *MRS Bulletin*, Autust 1998, pp. 23-25.

**Phulé. P. P.,** and **Ginder, J.M.** 1998. Synthesis and Properties of Novel Magnetorheological Fluids Having Improved Stability and Redispersibility. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 445-453.

**Phulé. P. P., Mihalcin, M. P.** and **Genc, S.** 1999. The Role of the Dispersed-Phase Remnant Magnetization on the Redispersibility of Magnetorheological Fluids. *J. Matr. Res.*, Vol. 14, No. 7, pp. 3037-3041.

**Phulé. P. P.,** 1999. Magnetorheological Fluid. American *Patent US 5,985,168*.

**Postrekhin, E. V.** and **Zhou, L. W.** 1998. Effective Medium and Electromagnetorhological Fluids. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 563-570.

**Qi, M.** and **Shaw, M. T.** 1997. Sedimentation-Resistant Electrorheological Fluids Based on PVAL-Coated Microbaloons. *J. Appl. Polym. Sci.*, V. 66, pp. 539-547.

**Rabinow, J.** 1948. Induced Fibration of Suspensions. *AIEE Trans.*, **67**:1308-1315.

**Rankin, P. J., Ginder, J. M.** and **Klingenberg, D. J.** 1998. Electro- and Magneto-rheology. *Current Opinion in Colloid & Interface Science*, **3**:373-381.

**Shimada, K., Fujita, T., Iwabuchi, M., Nishida, H. and Okui, K.** 1998. Braking Device and Rotating Regulator with ERF. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 680-686.

**Sohn, S. S.** 1996-a. Writing Method for Ink Jet Printer Using Electro-Rheological Fluid and Apparatus Thereof. *US Patent 5,510,817*.

**Sohn, S. S.** 1996-b. Electrostatic Hydrodynamic Jet Writing Method Using Electro-Rheological Fluid and Apparatus Thereof. *US Patent 5,576,474*.

**Sproston, J. L., El Wahed, A. K.** and **Stanway, R.** 1998. Electrorheological Fluids in Squeeze Under AC and DC Excitation. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 223-231.

**Takeda, H., Matsushita, K., Masubuchi, Y., Takimoto, J. I.** and **Koyama, K.** 1998. Mechanism of the Synergistic Effect in EMR Fluids Studied by Direct Observation. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 571-577.

**Tanaka, C., Mai, J., Nakagawa, M., Oshima, S., Yamane, R.** and **Park, M. K.** 1998. New Actuator Utilizing Phase Change of Functional Fluids. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 797-802.

**Tam, W. Y., Yi, G. H., Wen, W., Ma, H., Loy, M. M. T.** and **Sheng, P.** 1997. New Electrorheological Fluid: Theory and Experiment. *Phys. Rev. Lett.*, V. 78, pp. 2987-2990.

**Tang, X., Li, W. H., Wang, X. J.** and **Zhang, P. Q.** 1998. Structure Evolution of Electorheological Fluids Under Flow Conditions. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 164-171.

**Tang, X., Wang, X. J., Li, W. H.** and **Zhang, P. Q.** 1998. Testing and Modeling of an MR Damper in the Squeeze Flow Mode. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 870-878.

**Tang, X., Zhang, X.** and **Tao, R.** 2000. Enhance the Yield Shear Stress of Magnetorheological Fluids. *7th Int. Conference on Electrorheological (ER) Fluids and Magneto-Rheological (MR) Suspensions*, pp. 3-10.

**Umehara N., Shibata, I.** and **Edamura, K.** 2000. New Polishing Method with Magnetic Congelation Liquid. *7th Int. Conference on electrorheological (ER) Fluids and Magneto-Rheological (MR) Suspensions*, pp. 705-711.

**Vieira S. L., Nakano, M., Aizawa, R.** and **Ohashi, E.** 1999. Visualization of ER Fluid Microstructure in Oscillatory Slit Flow. *4th JHPS International Symposium on Fluid Power Tokyo'99*, pp. 371-376.

**Vieira S. L., Nakano, M., Henley, S., Filisko, F. E., Pompeo Neto, L. B.** and **Arruda, A. C. F.** 2000. Transient Behaviour of the Microstructure of Electrorheological Fluids. *7th* Int. Conference on electrorheological (ER) Fluids and Magneto-Rheological (MR) Suspensions, pp. 152-160.

**Volkova, O., Cutillas, S., Carletto, P., Bossis, G., Cebers, A.** and **Meunier, A.** 1999. Flow Induced Structures in Magnetorheological Suspensions. *Journal of Magnetism and Magnetic Materials*, 201, pp. 66-69.

**Volkova, O., Bossis, G., Carletto, P.,** and **Cebers, A.** 2000. Shear Banded Structures and Nematic to Isotropic Transition in MR Fluids. *7th Int. Conference on Electrorheological (ER) Fluids and Magneto-Rheological (MR) Suspensions*, pp. 358-365.

**Weiss, K. D., Carlson, J. D.** and **Nixon, D. A.** 1994. Viscoelastic Properties of Magneto- and Electro-Rheological Fluids. *Journal of Intelligent Material Systems and Structures*, Vol.5, pp. 772-775.

**Wendt, E.** and **Büsing, K. W.**1998. A New Type of Hydraulic Actuator Using Electrorheological Fluids. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 780-786.

**Whittle, M., Atkin, R. J.** and **Bullough, W. A.** 1998-b. Dynamics of a Radial Electrorheological Clutch. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 641-648.

**Winslow, W. M.** 1949. Induced Fibration of Suspensions. *J. Appl. Physics*, V. 20, pp. 1137-1140.

**Wolff, C.** 1996. Closed Loop Controlle ER-Actuator. 5th Int. Conference on Electro-Rheological Fluids, Magneto-Rheological Suspensions and Associated Technology, pp. 37-46.

**Wolff-Jesse, C.** and **Fees, G.** 1998. Examination of Flow Behaviour of Electrorheological Fluids in the Flow Mode. *Proc. Instn. Mech. Engrs.*, Vol.212, part 1, pp. 159-173.

**Yamamoto, H.** and **Nakano, M.** 2000. Dynamic Viscoelasticity and its Mechanical Model of an MR Suspension in Oscillatory Slit Flow Mode, *7th Int. Conference on electrorheological (ER) Fluids and Magneto-Rheological (MR) Suspensions*, pp. 665-673.

**Yokota, S., Kondoh, Y.** and **Yoshida, K.** 1996. Pressure Control Valves in Application of an Electrorheological Fluid (application to Drive a One-Link Manipulator). *Ninth Bath Int.Fluid Power Workshop*, September, pp. 229-245.

**Yokota, S., Yoshida, K.** and **Kondoh, Y.** 1999. A Pressure Control Valve Using MR Fluid. *4th JHPS International Symposium on Fluid Power Tokyo'99*, pp. 377-380.

**Yokota, S.,** and **Yoshida, K.** 2001. Development of Micro Control Valve Using Functional Fluid. *http://www.iijnet.or.jp/MMC/no.12/MicroValve.htm*, homepage date: March 16th, 2001.

**Yoshida, K., Kikuchi, M., Park, J. H.** and **Yokota, S.** 2001. A Micro ER Valve Fabricated by Micromachining. *Proc. of the 14th IEEE Intl. Conf. on MEMS*, Interlaken, Switzerland, pp. 467-470.

**Zhu, Y., McNeary, M., Breslin, N.** and **Liu, J.** 1998. Effect of Structures on Rheology in a Model Magnetorheological Fluid. *6th Int. Conf. on ER Fluids, MR Suspensions and Their Applications*, pp. 478-485.

**Zrínyi, M.** and **Szabó, D.** 2000. Muscular Contraction Mimiced by Magnetic Gels. 7th Int. Conference on electrorheological (ER) Fluids and Magneto-Rheological (MR) Suspensions, pp. 11-17.

**Ashish Agrawal**
Graduated in Mechanical Engineering from VJTI University of Mumbai (India) in 1999. Currently pursuing a master's degree in Mechanical Engineering at The University of Toledo.

**Prashant Kulkarni**
Got a Bachelor's degree in Mechanical Engineering from The University of Bombay, India, in 1999. Presently doing Master's in Mechanical Engineering at the University of Toledo (Ohio, USA) and working on the project "Driveline Analysis Software Development" for Dana Corporation. Area of research: magnetorehological fluids.

**Sheila L. Vieira**
Graduated in Chemical Engineering from Unicamp (Brazil), got her Master's degree in Petroleum Engineering and her Ph.D. in Mechanical Engineering from the same university. Worked one year in Caxias do Sul (Brazil) with plastics and wood recycling and 2 years at Yamagata University (Japan) as an Research Associate, teaching rheology to undergraduate students of Mechanical Engineering and researching about ER fluids. Since 2000 works at the University of Toledo (USA) at the Dynamic and Smart Systems Laboratory doing research on MR fluids.

**Nagi Naganathan**
Currently Professor and Interim Dean of the College of Engineering of The University of Toledo. He graduated with B.E. (honours) in Mechanical Engineering in 1978 from University of Madras (Regional Engineering College, Tiruchirapalli), M.S. in Mechanical and Industrial Engineering from Clarkson University in 1981, and a Ph.D. in Mechanical Engineering from Oklahoma State University in 1986. He is also the director of Dynamic & Smart Systems Laboratory at The University of Toledo in the M.I.M.E. Department.